CLEAN-UP AND RESTORATION OF URBAN ENVIRONMENTS AFTER VOLCANIC ERUPTIONS

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Disaster Risk and Resilience

by

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Keywords

Auckland Volcanic Field; Auckland, New Zealand; ballistic projectiles; building vulnerability; Calbuco volcano; clean-up; contingency planning; damage assessment; damage scale; debris; disaster; disaster recovery; disaster response; disaster risk management; disaster waste management; impact assessment; lahar; lava; monogenetic volcanic field; physical vulnerability; planning; pyroclastic density current; risk; risk assessment; tephra; volcanic ash; volcanic hazard.

Abstract

As urban development increases across the globe, societies are becoming more exposed to the negative effects of volcanic eruptions. Major cities exposed to volcanism, such as Auckland, New Zealand, require adequate disaster waste management processes to restore urban functionality following an eruption. Pre-event planning is critical to undertaking appropriate disaster waste management following a disaster. Modelling approaches are one the key methodological approaches to characterising and quantifying the effects of future disasters, and so are an important aspect of pre-event planning. Research investigating the interactions between the multitude of volcanic hazards and disaster waste management requirements is required to identify modelling approaches that can be used for pre-event planning purposes.

This thesis first uses case study analysis to contextualise disaster waste management after volcanic eruptions, with the intent of developing an evidence base and identifying important considerations for modelling and contingency planning. Scenarios are developed for the Auckland Volcanic Field (AVF) (The DEVORA Scenarios) using an interdisciplinary approach ensuring that key aspects of AVF volcanism are captured and scenarios are usable for a variety of disaster risk reduction activities, including modelling disaster waste clean-up requirements. Finally, a modelling framework is developed to assess disaster waste clean-up in urban environments. The DEVORA Scenarios are used to demonstrate the utility of this approach.

The findings suggest that the spectrum of different hazards and their unique processes pose a considerable difficulty to managing waste after volcanic eruptions. Specific management requirements include the properties of some volcanic waste products (e.g., lava), large volumes of highly mixed waste streams, and long durations of volcanic activity with substantial uncertainty on the timing and end of waste generating events. Modelling outputs indicate that 11-14x10^6 tonnes of building debris generated from the scenarios, but the median is 2-3x10^6 tonnes. Substantial quantities of tephra will require removal (1.5 – 12x10^9 tonnes). In the event of a future AVF eruption waste streams and quantities are likely to put intense stress and exceed existing waste processing and handling facilities in Auckland.

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I have been privileged to have had the opportunity to learn from other scientists, researchers, and disaster risk reduction practitioners from around the world. Associate Professor Carol Stewart provided supportive comments and encouragement on everything to do with volcanic impacts. Dr. Richard Smith and Richard Woods were friendly sounding boards for some of my research ideas at various workshops and forums over the years, which I am grateful for. I owe thanks to Lizette Bertin and Rodrigo Calderón of SERNAGEOMIN for all their support in Chile and beyond. Dr. Jane Rovins, Dr. Susanna Jenkins, Dr. Christina Magill, Prof. Russell Blong, Prof. Peter Baxter, and Prof. Constanza Bonadonna have all provided support and valuable guidance along the way.

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Chapter 2 – An overview of volcanic hazards and disaster waste management

Prepared for submission to: *International Journal of Disaster Risk Reduction*

Please detail the nature and extent (%) of contribution by the candidate:
Mr. Hayes conceived the idea of the manuscript, conducted all background research and analysis and wrote the manuscript (95%). Dr. Brown and Dr. Wilson provided feedback on drafts of the manuscript (5%).

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Chapter 3 – Tephra clean-up after the 2015 eruption of Calbuco volcano, Chile: A quantitative geospatial assessment in four communities

Published: *Journal of Applied Volcanology*

Please detail the nature and extent (%) of contribution by the candidate:

Mr. Hayes conceived the idea of the manuscript, conducted data collection in Chile. Mr. Hayes designed the methodological approach and modelling framework, and conducted all modelling. Mr. Hayes wrote the manuscript, with co-authors providing general feedback on draft versions of the manuscript. and wrote the manuscript. All co-authors contributed to data collection in Chile and Argentina. Mr. Hayes handled all manuscript revisions required for publication.

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Chapter 4 – Timber-framed Building Damage from Tephra Fall and Lahar: 2015 Calbuco Eruption, Chile

Published in: Journal of Volcanology and Geothermal Research

Please detail the nature and extent (%) of contribution by the candidate:
Mr. Hayes wrote the draft manuscript, conducted the data analysis, and handled peer review comments from journal reviewers (60%). Mr. Calderon assisted with translations and liaising with Chilean authorities. Assoc. Prof Wilson, Asst. Prof Jenkins, Drs Deligne and Leonard drove the development of the methodological approach, with input from Mr. Hayes and other co-authors. All authors provided feedback on the manuscript. Mr. Hayes handled all reviewer comments, with guidance from other co-authors.

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Chapter 5 –Developing a Multi-hazard Volcanic Eruption Scenario Suite Using an Interdisciplinary Approach

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The submitted manuscript was written by Josh L. Hayes. The methodological approach and conceptual development of the manuscript were developed by Josh L. Hayes, involving discussions with Natalia I Deligne, Thomas M Wilson and Graham S. Leonard. These discussions involved Josh presenting proposed methodological approaches to scenario development, with supervisors helping refine them. Josh L. Hayes organised the stakeholder workshop, developed all workshop materials (question sets, early scenario drafts, presentation material), sent invitations to appropriate workshop participants (with guidance from Thomas Wilson and Natalia Deligne), solely facilitated the workshop, and synthesised all workshop data (presented in DEVORA Scenarios report – Appendix C). Josh then used the workshop feedback to revise the scenarios. Josh conducted the detailed literature review that informed the scenario storylines and hazard modelling. Josh conducted all scenario storyboarding. Josh conducted all hazard modelling of the scenarios, with the exception of ballistics and lava flow modelling, which Rebecca Fitzgerald and Sophia Tsang conducted with input and guidance from Josh. All co-authors reviewed draft versions of the manuscript and provided feedback, which Josh then implemented.

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Chapter 6 –Modelling Disaster Waste Generation From Volcanic Events
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The submitted manuscript was compiled and written by Josh L. Hayes. Conceptual approaches of the manuscript were developed by Josh L. Hayes, involving discussions with Natalia I Deligne, Thomas M Wilson and Charlotte Brown. Josh L. Hayes developed the modelling framework, conducted all modelling. All co-authors reviewed draft versions of the manuscript.

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Appendix A – Impacts of the 2015 eruption of Calbuco volcano on Chilean infrastructure, utilities, agriculture, and health

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Josh L. Hayes was lead author – he heavily contributed to field data collection and wrote most of the report. Josh L. Hayes coordinated and compiled the report and edited the entire report following reviews of draft sections from NI Deligne (Agriculture), John B. Wardman (Electricity and telecommunications), Carol Stewart (Public health), Lizette Bertin (Volcanic hazards in Chile), and Rodrigo Calderon (Characteristics of study area). Other co-authors (TM Wilson, GS Leonard, KL Wallace, and PJ Baxter) contributed to field data collection, and/or reviewing sections of the report where their area of expertise most suited. NI Deligne conducted revisions following peer review.

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Appendix B – The DEVORA Scenarios: Multi-hazard eruption scenarios for the Auckland Volcanic Field

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Josh Hayes was lead author and conceptualised, compiled and wrote the majority of the report. He also conducted all modelling (with the exception of ballistics and lava flows) and data analysis. Sophia Tsang conducted all lava flow modelling. Daniel Blake contributed to early scenario development. Natalia Deligne, Angela Doherty, Jenni Hopkins, Tony Hurst, Nicolas Le Corvec, Graham Leonard, Jan Lindsay, Craig Miller, Karoly Nemeth, Elaine Smid, James White and Thomas Wilson reviewed the manuscript and contributed their specialised knowledge to the report.

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Chapter 1: Introduction

The aim of this thesis is to improve understanding of clean-up and disaster waste management issues after volcanic eruptions. This introductory chapter is structured to introduce the conceptual framework of Disaster Risk Reduction, followed by a discussion of waste management after disasters and the current state of research. I then discuss volcanic eruptions and why disaster waste management is an important research gap. I then introduce the study area of Auckland, New Zealand, as a case study for the thesis. I finish this chapter by outlining the thesis aims and objectives, and how the following chapters of this thesis are structured.

1.1 DISASTER RISK REDUCTION

Reducing the effects of disasters on society is an important focus of sustainable development globally (United Nations 2012; Pelling et al. 2014). However, both the frequency and severity of disasters has been increasing worldwide (World Bank 2012). Disaster risk represents the possibility of future adverse effects (e.g., loss of life, economic losses) (Cardona et al. 2012). There are three variables that drive disaster risk: hazard, exposure, and vulnerability (Crichton 1999; Alexander 2000). According to the United Nations General Assembly (UNGA) (2016), exposure is the elements at risk, such as people, land, and infrastructure; hazard is the potentially damaging phenomena, such as earthquakes, volcanic eruptions, or severe weather events; vulnerability is the susceptibility and capacity of the elements at risk impacted by hazards. Recent investigations of disaster losses suggest the most substantial driver of recent increases in disaster losses are related to changes in exposure due to increased urbanisation and economic development (Bouwer et al. 2007; Barredo 2009; 2010; World Bank 2012; Cardona et al. 2012; Mohleji and Piekle Jr. 2014; Visser et al. 2014).

1.1.1 Best practices in disaster risk reduction

The Sendai Framework

The United Nations Sendai Framework is a 15-year global framework for disaster risk reduction (UNISDR 2015). It recognises the role of the state in disaster risk reduction, along with a variety of stakeholders (e.g., insurance industry, infrastructure groups, emergency managers). The primary aim of the framework is "*the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries*" (UNISDR 2015, p12). To achieve this aim, there are four priority areas for action:

1. Understand disaster risk;
2. Strengthen disaster risk governance to manage disaster risk
3. Invest in DRR for resilience
4. Enhance disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction.

Using risk information to inform decision-making

In order to meet the goals of the Sendai Framework, risk information must inform decision-making (Simpson et al. 2014; Fraser et al. 2016; Murnane et al. 2016). Identification of risk is one of the critical components that informs decision-making because it makes decision-makers aware of the types and scales of risk they face and allows for it to be contextualised with a myriad of other societal issues they must manage (Simpson et al. 2014; Murnane et al. 2016). Risk information can also help decision-makers reduce risk through the development of structural (e.g., construction of flood dams, earthquake resistant buildings) and non-structural measures (e.g., land use planning, warnings and evacuations) (Simpson et al. 2014). Contingency measures such as the development of early warning systems or identification of evacuation routes rely upon accurate information on the likely geographic area to be affected (Simpson et al. 2014). Through accurate quantification of risk, it is possible to develop financial protection mechanisms (e.g., insurance) (Simpson et al. 2014).

Understanding the potential impacts of a disaster before an event or rapidly following the event can assist with immediate identification needs for relief and recovery efforts. Thus, risk information is an essential component of managing risk across a variety of sectors. Global experience indicates that it is important that risk assessments generate information that is credible, legitimate, and relevant to communities at risk (Simpson et al. 2014; Beaven et al. 2017). To do so requires consideration of each of the three components of risk (Crichton 1999; Figure 1.1): hazard, exposure, and vulnerability.

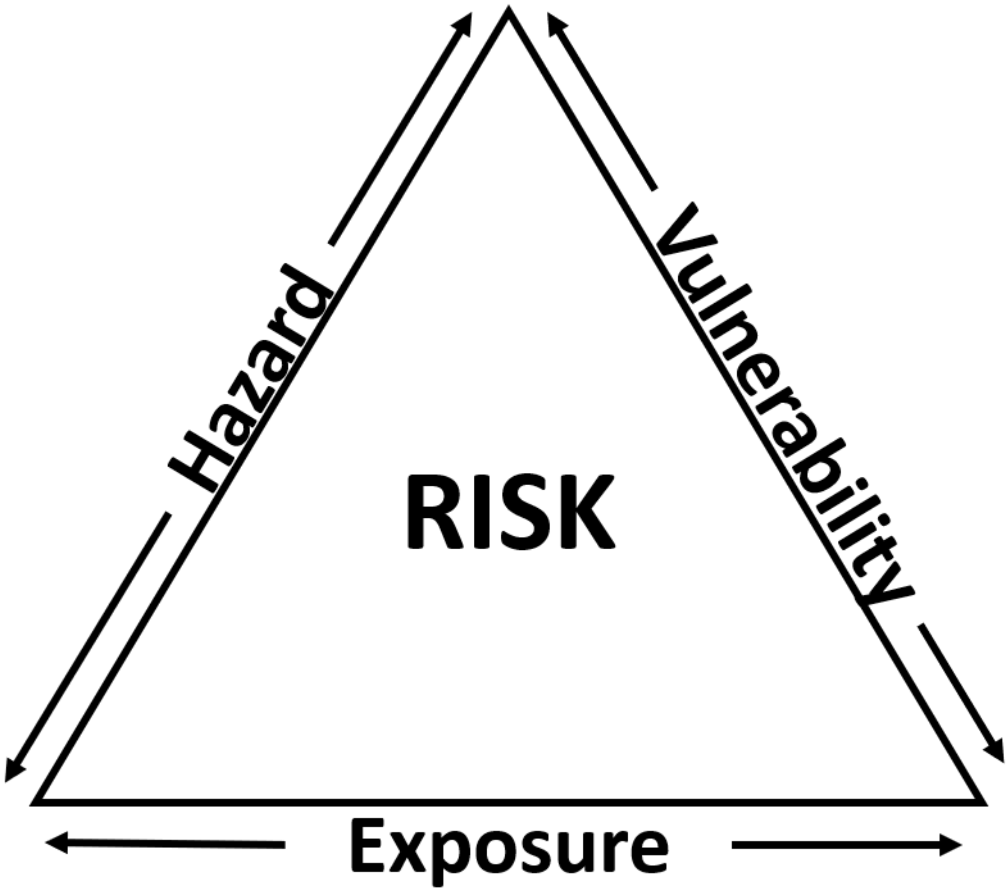

Figure 1.1: Risk triangle (based on Crichton 1999)

Hazard assessments

Hazard assessments require characterising potential hazards that may affect an area of interest. Hazard assessments can be deterministic or probabilistic. Deterministic (scenario) hazard assessment (DHA) aims to characterise a single outcome based on a set of fixed input parameters (Terlien et al. 1995; Panza et al. 1998; Jelínek and Wagner 2007). Probabilistic hazard assessment aims to characterise all possible outcomes based on statistical relationships (Cornell 1968; Russell 1971; McGuire 1995; Marzocchi et al. 2004). Choosing whether to undertake a deterministic or probabilistic approach relies upon the context of the study (e.g., data availability, time sensitivity of the analysis, project output requirements, and intended applications) (Romeo and Prestininzi 2000; McGuire 2001; Bommer 2002; Thompson and Frazier 2014). Hazard assessments typically have four components: magnitude (how big will the event be?), frequency (how often does the event occur?), spatial extent (how big an area will be affected?), and intensity (how strong will the event be in space and time?). Magnitude can often be obtained through geological and geomorphological studies identifying the magnitude of previous events (Jansen 2006; Pyle 2015). Frequency usually requires analysis of historical or geological data sets to identify how often events occur (Moore 1990; Jones et al. 1999; Corominas and Moya 2008; Deligne et al. 2009). 'Hazard curves' can be created by combining the frequency and magnitude into frequency-magnitude graphs, which is a key component of probabilistic hazard analysis (e.g., Stedinger and Cohn 1986; McGuire 1995; Hungr et al. 1999; Mason et al. 2004; Geist and Parsons 2006). The spatial extent of hazard and intensity can be obtained through field studies and/or analytical or numerical models that consider a variety of spatial data and factors that are related to the hazard (e.g., physics, geology, landscape morphology, hydrology) (Malin and Sheridan 1982; Carey 1996; van Westen et al. 2008). Therefore, comprehensive hazard assessment requires a diverse range of data that must be collected and expertly utilised (Simpson et al. 2014).

Exposure assessments

Exposure assessment requires identifying the elements at risk in areas exposed to hazards (UNISDR 2009). Exposure is a critical component of risk information as empirical evidence suggests the greatest output of loss estimates within risk models derives from exposure data (e.g., Spence et al. 2003; Chen et al. 2004; Lavakare and Mawk 2008; Bal et al. 2010). Exposure information can be collected using techniques such as full enumeration (each exposed asset in a study area fully detected and defined), sampling (summary statistics for a large area estimated based on smaller subset areas) and using proxy data (e.g., night-time light data as proxy for population density) (Simpson et al. 2014). Full enumeration is the most detailed but can be time consuming and expensive to conduct (Simpson et al. 2014). Exposure assessments can be conducted at spatial scales from local to global. Local scale assessments often rely upon crowd sourced data (e.g., Open Street Map - https://www.openstreetmap.org) (Murnane et al. 2016). There is also increasing interest in utilising unmanned aerial vehicles (UAVs) and mobile technology to capture exposure data (Bengtsson et al. 2011; Deville et al. 2014 Yu et al. 2018). In rare situations local scale infrastructure is officially compiled, but this is usually limited to countries with developed economies (Simpson et al. 2014). Global scale assessments are useful for exploring long-term temporal trends and comparing exposure across global regions (Peduzzi et al. 2009; Jongman et al. 2012; Peduzzi et al. 2012; Hallegate et al. 2013; De Bono and Mora 2014; Brown et al. 2015). There are several types of information that can be included within a comprehensive exposure model such as: population (e.g., demographic characteristics), property (e.g., construction types), agriculture (e.g., land-use characteristics), transportation (e.g., road types), critical infrastructure and facilities (e.g., hospitals, electricity distribution lines) (Simpson et al. 2014).

Vulnerability assessments

There are a number of dimensions to vulnerability (e.g., physical vulnerability, human vulnerability, socio-economic vulnerability, systemic vulnerability), each with intrinsic links to the seven community capitals (human, social, political, cultural, built, natural, and financial) (Pigg et al. 2013). Physical vulnerability characterises the susceptibility of physical assets such as buildings, critical infrastructure to damage or disruption from a hazard or hazards and is perhaps the most widely applied vulnerability dimension due to the relative simplicity of integrating it within risk modelling frameworks (Douglas 2007). Physical vulnerability can be assessed through the collection of empirical data sets of damage and then the development of empirically based statistical relationships between hazard intensity (e.g., flood height, wind speed, ground acceleration) with a corresponding measure of damage (e.g., monetary losses, percentage damage to a building) (Douglas 2007). However, due to the relative scarcity of damaging events that can be assessed compared to the variability of construction types and standards evident within communities and across the world, empirical data sets can be difficult to obtain at the required levels of data quality and quantity for robust statistical relationships to be developed (Rossetto and Ioannou 2018). Laboratory experimentation, theoretical/conceptual model development, and selective heuristics (i.e. expert elicitation) have also been used to characterise relationships between hazard intensity and physical vulnerability of assets (Spence et al. 2005; Marqsood et al. 2014; Blake et al. 2017a). Human vulnerability uses similar approaches as physical vulnerability to determine the susceptibility of humans to the physical effects of hazards (e.g., fatality/casualty rates: Peduzzi et al. 2009). Socio-economic vulnerability is the vulnerability of socio-economic systems to the effects of hazards and is perhaps the most complex and challenging to integrate within standard risk modelling frameworks (Zoppou et al. 2004; Haynes et al. 2008; Armas and Gavris 2013). Socio-economic vulnerability uses indexes and indicators made up of demographic and socio-economic data to characterise vulnerability to hazards, which vary considerably between communities (Cutter et al. 2003; Zoppou et al. 2004). Systemic vulnerability is the vulnerability of systems to the effects from hazard exposure, which can occur due to direct damage to a component of the system or indirect effects from a physical, functional, or organisational failure from an interdependent system (Menoni et al. 2002; Hellström 2007). Thus, the data requirements and assessment methodologies for vulnerability are diverse, complex and require multi-disciplinary teams of researchers to conduct comprehensive vulnerability assessments.

Interdisciplinarity and collaborative research practices in disaster research

Interdisciplinary and collaborative research is a core value of disaster related research. For example, the diversity of information and approaches outlined above to developing hazard, exposure, and vulnerability information for risk assessments necessitates interdisciplinary research methodologies (Faber et al. 2014; Simpson et al. 2014; Gall et al. 2015; UNISDR 2015; Ismail-Zadeh et al. 2017; Martinez et al. 2018). In addition, there are important considerations that related to ethics, research rigour, and risk information usability that are integral to disaster research that necessitate interdisciplinary and collaborative research practices. I will briefly outline these below.

A longstanding element of disaster research has been to document and analyse empirical observations from areas affected by disasters (Killian 1956). This often requires scientists to visit areas affected by disasters to collect data. However, Gaillard and Gomez (2015) have criticised the modern ‘research gold rush’ that has emerged during and following disasters, pointing out that it can led to adverse outcomes for affected communities. For example, Missbach (2011) highlighted that Aceh, Indonesia was "ransacked" by international researchers in the aftermath of the 2004 tsunami, with local researchers excluded or relegated to assistant roles. Similar issues have been described in Sri Lanka following the 2004 tsunami (Brun 2009). Beaven et al. (2015) illustrates that it is important that post-disaster research is undertaken in a coordinated manner to reduce negative outcomes on affected communities as influxes of international researchers can strain limited resources. Kelman (2005) suggested that principles of good governance: participation, transparency, accountability, rule of law, effectiveness, and equity, could be important aspects of operational ethics used in disaster studies. In addition to the ethical issues of foreign researchers flying in to conduct disaster research, there are important considerations for the validity and quality of the research. For example, the rapid convergence of researchers with limited contextual knowledge of the study area can lead to misinterpretations (Killian 1956; Gomez and Hart 2013). Gaillard (2018) has suggested that a paradigm shift is required in disaster studies to ensure that local researchers are able to investigate local disasters. This importantly allows: (1) local research communities that best understand the local context, leading to better research outcomes; (2) capacity building in disaster research; and (3) lessons to be learned from those that have first-hand experience with disasters. Thus, embedding local researchers within post-disaster research teams is of critical importance from both ethical and research validity perspectives.

It is fundamental that forward-looking disaster risk information is legitimate, relevant, and credible if stakeholders are to make use of it (Cash et al. 2002; McNie 2007; Simpson et al. 2014; Beaven et al. 2017). Co-development of risk information with a variety of stakeholders has been a successful approach to ensure that information is useful for stakeholders. For example, Davies et al. (2015) suggested that scientists co-produce of disaster scenarios with local communities, government officials, and civil society organisations so that long-term disaster plans could be produced. Such an approach helps facilitate improved risk governance and coordination across relevant stakeholders (UNISDR 2015). A co-development process has been undertaken in 'Project AF8', a project designed to develop a collective emergency response plan for the South Island, New Zealand, for a potential earthquake on the Alpine Fault (Orchiston et al. 2018). Thus, co-production and stakeholder engagement is an accepted and well utilised approach to disaster risk information production globally, and is currently being applied within a New Zealand context.

1.2 WASTE MANAGEMENT AND DISASTERS

Waste management systems have evolved over human history from the completion of the Roman Cloaca Maxima in the 7th-6th century BC to 19th century London dust-yards to development of comprehensive environmental protection policies from the 1960s (Velis et al. 2009; Barles 2014). Modern waste management has evolved into a complex system that is a vital part of protecting human health, the environment, and resource conservation (Dyson and Chang 2005; Zimring and Rathje 2012; Guerrero et al. 2013).

When disasters occur, large quantities of waste can be generated within a relatively short time window, placing stress on waste management systems (Reinhart and McCreanor 1999; Basnayake et al. 2006; Brown et al. 2011). Disaster waste products such as construction and demolition debris, hazardous chemicals (e.g., pesticides and cleaning agents), and unconsolidated material (e.g., liquefaction ejecta, mud, sand, and tephra) are contributors to the negative impacts of disasters: they hinder emergency response and urban recovery efforts (Kobayashi, 1995; Brown et al., 2011). Construction and demolition debris can obstruct site access for emergency workers and present a health and safety hazard due to unstable rubble piles or exposure to asbestos-containing (and other hazardous) materials (Brown et al., 2011). Disposal of hazardous chemicals must be handled with care, sometimes by highly specialised contractors, which can prolong recovery efforts (Brown et al., 2011). Unconsolidated material (e.g., liquefaction ejecta and tephra) can cover large areas and cause considerable disruption to transport, water supply, waste water, and electricity networks (Blong 1984; Villemure et al. 2012; Wilson et al. 2012; Wilson et al. 2014). In some situations, the presence of large quantities of unconsolidated material has led to public health issues such as respiratory, skin, and eye irritations (Horwell and Baxter 2006; Brown et al. 2011). Therefore, disaster waste management is a critical aspect of recovery and is important to manage well as poor waste management practices have been found to slow recovery efforts (Brown et al. 2011; Hatcher et al. 2012).

To provide better guidance on disaster waste management decision-making it is necessary to develop a large evidence base that evaluates how disaster waste can be managed in a variety of disaster conditions (Brown et al. 2011). The publication of case studies on disaster waste management have provided useful insights into management requirements and challenges associated with disaster waste (Brown et al. 2011). Case studies have reported on disaster waste management for specific countries (e.g., Faleschini et al. 2017; Francesco et al. 2018) or overall post-disaster lessons learned documents and publications (e.g., Pilapitiya et al. 2006; Luther 2008; Domingo and Luo 2017; Karunasena et al. 2012; Norton et al. 2018; Poudel et al. 2019). Others have reported on specific considerations within the disaster waste system, such as policy (e.g., Roper 2008), social effects (e.g., Kawamoto and Kim 2016), municipal coordination (e.g., Miyazaki and Sato 2017), waste characteristics (e.g., Shibata et al. 2012; Murasawa et al. 2013), waste treatment (e.g., Saffarzadeh et al. 2017; Sakai et al. 2018) and disposal (e.g., Sasao 2016).

Planning is considered an important disaster preparedness strategy for disaster waste management (Crowley 2017; Crowley and Flachsbart 2018). One of the most important aspects of planning for disaster waste is to understand the potential quantities and composition of waste likely to be generated from future disasters (USEPA 2008; Johnston et al. 2009; Brown et al. 2011; UNOCHA 2011). There has been considerable effort placed on pre-identifying the compositions and quantities of waste expected post-disaster using a variety of approaches. This information can inform planning regarding necessary resources. Empirical approaches using historical waste data and hazard intensities have been used to forecast waste quantities, but these approaches rely upon data collection from past events and are rarely transferable to different areas (Chen et al. 2007; Hirayama et al. 2010 a, b; FEMA 2013). Combining approaches that model damage with the likely waste generated under different degrees of damage has also been conducted (Tanikawa et al. 2014; García-Torres et al. 2017; Tabata et al. 2017, 2018; Leader et al. 2018). This conceptual approach is useful for pre-event planning but requires detailed hazard, exposure and vulnerability information of the affected community. Although the outputs of these models appear credible, few have been tested in real word disaster conditions (Xiao et al. 2012; Tanikawa et al. 2014).

A challenge with being able to compare disaster waste modelling approaches with real world disaster information is that there are substantial inconsistencies in the documentation and reporting of this information in the literature (Brown et al. 2011). For example, the reporting of post-disaster waste streams and quantities are often aggregated and reported using different units (e.g., cubic metres or tonnes), which makes it difficult to make comparisons across case studies (Brown et al. 2011). The underlying data and methodological approaches conducted are often not reported, which undermines the estimates reliability. Unambiguous reporting of post-disaster waste quantities and transparent documentation of the methodological approaches and underpinning data used for their estimation are required.

Several studies have explored decision-making optimisation through numerical modelling and development of a proliferation of algorithms, particularly towards the logistics of disposal site locations and waste handling for earthquakes and hurricanes (Table 1.1). Guidance around disaster waste management model development has been framed dominantly under assumptions of earthquake and hurricane disasters (Rafee et al. 2008). Comparatively, little attention has been given towards other disaster events such as volcanic eruptions.

A disaster waste management planning tool is currently being developed specifically for New Zealand (called the New Zealand Disaster Waste Management Planning Tool (NZDWMPT) throughout this thesis). The purpose of the NZDWMPT is to help regions in New Zealand to plan for solid waste management following disasters. The NZDWMPT is designed for organisations that whose responsibility it is to lead or assist with disaster waste management (e.g. regional and local government, waste contractors, Civil Defence and Emergency Management). The NZDWMPT currently includes two reports that outline key planning requirements that should be undertaken before, during, and following disasters. The first report provides a planning template that users should follow to plan for disaster waste management in New Zealand. A final aspect of the NZDWMPT, yet to be completed and become operational, is a geospatial modelling tool. This tool is envisioned to allow modelling of potential disaster waste scenarios at a regional scale to identify potential waste streams and quantities requiring management.

Table 1.1: Disaster waste decision optimisation models

Study name	Study location	Hazard(s)	Model description
Fetter and Rakes (2012)	Chesapeake, Virginia, USA	Hurricane	Disaster waste recycling facility location identification model to minimise the average cost of locating facilities to assist with disaster response planning.
Pramudita et al. (2014)	Tokyo, Japan	Earthquake and flood	Disposal transportation routing decision optimisation when paths are blocked by debris.
Hu and Sheu (2013)	Wenchuan, China	Earthquake	Minimising environmental and operational risks and psychological trauma caused by disaster waste management.
Onan et al. (2015)	Istanbul, Turkey	Earthquake	Siting of temporary disposal locations that considers financial costs and side effects on humans.
Habib and Sarkar (2017)	Karachi, Pakistan	Hurricane	Assigning disaster waste generated throughout a city to a temporary waste management site based on a sustainable supply chain.
Lorca et al. (2017)	Miami-Dade County, Florida, USA	Hurricane	Optimisation of time and costs of selecting processing sites, selection of processing capacities, and waste flow decision-making for collection, transportation and disposal.
Wakabayashi et al. (2017)	Mie Prefecture, Japan	Earthquake	Optimisation of disaster waste transportation routes to temporary storage sites, incineration plants, and landfill.
Boonmee et al. (2018)	None	Hazard generic, but uses assumptions from hurricanes	Optimising the costs (financial, environmental, and human) and revenue from managing disaster waste.
Cheng et al. (2018)	Queensland, Australia	Bushfire	Maximising the reliability of a disaster waste management system (completing clean-up within a target time and cost).

1.3 VOLCANIC ERUPTIONS

Volcanic eruptions are the physical process of molten rock, ash, and gas being discharged from a volcanic vent and they can vary widely in their magnitude, duration, and physical phenomena (Siebert et al. 2015). A variety of different hazards can manifest from volcanic eruptions and they can complexly interact and potentially cascade with and from one another (Tierz et al. 2017). For example, large deposition of unconsolidated volcanic deposits into catchments due to the occurrence of pyroclastic density currents (PDCs) or tephra fall can remobilise during later rainfall events to form lahars, which can affect downstream areas for years (Major 2004; Gran et al. 2011; Pierson et al. 2013). Volcanic hazards can be limited to within a few kilometres of an active vent to hundreds of kilometres from the vent (e.g., tephra fall deposition) and from the Earth's surface into the stratosphere.

Volcanoes have a long history of affecting human society. To exposed communities, volcanic eruptions have the potential to cause loss of life and livelihoods, damage or disrupt infrastructure and buildings, and cause ongoing public health hazards (Baxter, 1990; Baxter et al., 2005; Blong, 1984; Horwell and Baxter, 2006; Wilson et al., 2012; Wilson et al., 2014). These impacts can be: (a) relatively short term through one off eruptions, (e.g., Calbuco, Chile April-May 2015: Hayes et al. 2019 – See Appendix A) (b) because of prolonged eruptive episodes causing sustained displacement of affected communities (e.g., Soufrière Hills, Monserrat 1995 – 2003 and 2005 – 2013: Sword-Daniels et al. 2014). In some cases, the effects have been felt for years after the eruptive activity has ceased (e.g., Hudson, Chile 1991) (Blong, 1984; Jenkins et al., 2007; Magill et al., 2013; Sword-Daniels et al., 2014; Wilson et al., 2011; Wilson et al., 2012). Approximately 280,000 fatalities have occurred from volcanic eruptions since 1500 AD, with 80% occurring within 20 km of the volcano (Brown et al. 2017). It is currently estimated that 30 million people live within 10 km of a volcano, over 220 million within 30 km, over 800 million within 100 km, and over 20 capital cities within 30 km (Brown et al. 2015). Thus, assessing risk and evaluating potential risk reduction activities for communities exposed to volcanism are critical to reducing disaster risk globally.

Volcanic hazard assessment has received substantial consideration, but there is increasing acknowledgement of the importance for obtaining a greater understanding of vulnerability in the context of volcanoes to further improve volcanic risk assessment

(Jenkins et al. 2014; Wilson et al. 2012; Wilson et al. 2014; Bonadonna et al. 2018). Specific priority areas of inquiry are (Bonadonna et al. 2018):

- Improved characterisation of various dimensions of vulnerability (e.g., physical, socio-economic, and systemic) and how they change before, during, and after volcanic eruptions.
- Identifying vulnerability dimensions that contribute the most to volcanic risk.
- Assessing vulnerability and volcanic impacts in the context of cascading and multi-hazard environments as well as compounding physical, social, and economic consequences.
- Continued and iterative collection of post-disaster volcanic impact information and forensic investigations to develop a strong international evidence-base.
- Identification of potential cascading impact chains.
- Identification of effective adaptation actions during long-lived eruptions or at frequently erupting volcanoes.
- Investigations into how societies recover after volcanic eruptions.

A key topic that contributes to several of the above priority areas is the analysis of clean-up and disaster waste management after volcanic eruptions. To date, there has been work on the clean-up of tephra deposits in urban areas after volcanic eruptions and the importance of disposing this waste (Blong 1984; Johnston et al. 2001; Dolan et al. 2003; Wilson et al. 2012; Hayes et al. 2015). There has been no work conducted on other disaster waste types that can be generated from volcanic activity. However, volcanic eruptions within the last few decades have demonstrated the challenging post-eruption environments that communities must cope with to recover from volcanic eruptions. For example, Rabaul Town, Papua New Guinea, was severely damaged following the eruption of Tarvurvur and Vulcan in 1994 (Blong and McKee 1995). Plymouth, on the island of Montserrat, was abandoned after being completely devastated by pyroclastic flows from the eruptions at Soufrière Hills volcano 1995-2003 (Baxter et al. 2005). Thus, despite numerous instances of communities needing to clean-up and manage waste following volcanic eruptions, there has been little to no consideration of clean-up and disaster waste management requirements after most volcanic hazards. This is the central theme of this thesis.

1.4 THE APRIL-MAY 2015 CALBUCO VOLCANIC ERUPTION

It is necessary to document and analyse volcanic impacts that occur throughout the world so that a strong evidence base can be developed, which can be used to inform forward-looking disaster risk reduction activities (e.g. developing vulnerability models). Systematic documentation of volcanic impacts has become an important strategic focus of volcanic risk research in New Zealand, with numerous reconnaissance efforts across the world (Wilson et al. 2012). The Calbuco volcanic eruption, which affected communities in Chile and Argentina is used as a case study in places throughout this thesis. This eruption is used because it provided a useful opportunity within the scope and timeframe of this thesis to report on and analyse the impacts and disaster waste management issues it led to. The purpose of using the Calbuco case study is to fill in some of the knowledge gaps outlined in section 1.3, most importantly a lack of detailed analysis of disaster waste management following volcanic eruptions and limited empirical analysis of building damage after volcanic eruptions.

1.5 AUCKLAND, NEW ZEALAND CONTEXT

Auckland City, New Zealand, is one of the few cities in the world built on top of a volcano with a population of over one million people (Brown et al. 2015). Thus, Auckland is an ideal case study area to investigate clean-up and disaster waste management planning requirements because of the complex volcanic risk environment, which I outline in the subsections below.

1.5.1 Volcanic risk in Auckland

Auckland is New Zealand’s most populated city (population ~1.7 million: Stats NZ Tatauranga Aotearoa 2017a) and is an important hub for the New Zealand economy (Stats NZ Tatauranga Aotearoa 2017b). Auckland is exposed to several natural hazards (e.g., tsunami, earthquake, flooding, slope instability, volcanism) (Edbrooke et al.

2003). Volcanic hazard exists, both through the monogenetic Auckland Volcanic Field (AVF) (Searle 1964; Kermode 1992; Allen and Smith 1994) and distal sources of tephra (Sandiford et al. 2001, Shane and Hoverd 2002, Molloy et al. 2009, Zawalna-Geer et al. 2016). The Department of Prime Minister and Cabinet (DPMC) lists an eruption in Auckland as one of New Zealand's major national security threats (DPMC 2011). The Auckland Emergency Management (AEM) group plan lists a volcanic eruption in the AVF or distal tephra fall as a high priority hazard requiring management (on a scale of very high priority, high priority, moderate priority, and low priority) (Auckland Council 2016). The Lloyd's City Risk Index (2018) ranks a volcanic eruption as the third largest threat to Auckland City as a function of Gross Domestic Product (GDP) at risk, behind a market crash and flooding. Research using economic models to investigate direct business inoperability economic costs of an AVF eruption indicate they are likely to exceed NZ$1 billion and potentially as high as NZ$10 billion, but indirect effects on the economy could be far greater (McDonald et al. 2017). Damage to the residential housing stock and contents has been modelled as high as NZ$8.7 billion, but this is just one potential scenario (Deligne et al. 2017a). Critical infrastructure and utilities are likely to be severely disrupted in parts of Auckland affected by volcanic hazards (Johnston et al. 1997a, b; Johnston et al. 2001; Daly and Johnston 2015; Deligne et al. 2017b; Blake et al. 2017b). Depending on the eruption location, large numbers of people may be evacuated from parts of Auckland (Blake et al. 2017b). Thus, Auckland, New Zealand, is a complex volcanic risk environment and serves as a useful study area for quantifying and characterising the disaster waste clean-up requirements for planning in the event of a future AVF eruption.

Auckland Volcanic Field (AVF)

There are 53 identified eruptive centres within the Auckland Volcanic Field (AVF) (Figure 1.2). Some of these centres can be observed today as cones and maars that have been formed since activity in the field initiated at 193.2 ± 2.8 ka (Kermode 1992, Hayward et al. 2011; Leonard et al. 2017). Ellipsoidal, rectangular, and convex hull shapes have been used to represent the maximum extent of the AVF for a variety of different applications (Spörli and Eastwood 1997; Bebbington and Cronin 2011; Sandri et al. 2012; Le Corvec et al. 2013a; Runge et al. 2015). The extent, although uncertain, is usually represented as a 320 km^2 ellipse because a mantle source zone below a volcanic field will be susceptible to a stable heat source that is usually semi-circular in plan view (Fedotov 1981; Condit and Connor 1996; Runge et al. 2015). There does not appear to be any spatio-temporal evolution of vent opening within the field, meaning the next eruption could occur anywhere within the AVF (Bebbington and Cronin 2011; Le Corvec et al. 2013b; Leonard et al. 2017). The most recent eruption within the AVF (Rangitoto ~600 years ago: Needham et al. 2011; Leonard et al. 2017), the overall age of the AVF in comparison with lifespans of analogue volcanic fields (e.g., Büchner et al. 2015), and the presence of a mantle anomaly at depths of about 70–90 km (Horspool et al. 2006), indicate the field will likely erupt again (Lindsay 2010). Repose periods range from <0.5 k.y to 20 k.y and evidence exists of a clustering of activity throughout the field around 30-34 ka (Molloy et al., 2009; Leonard et al. 2017). An AVF eruption is considered a low probability (0.03 – 0.08 annual exceedance probability) but high consequence event (Molloy et al., 2009; Hurst and Smith 2010; Leonard et al. 2017).

Geologic mapping and physical volcanology studies find that both magmatic and phreatomagmatic eruption styles occur in the AVF (Allen and Smith 1994; Lindsay 2010; Kereszturi et al. 2014). Interpretations of the geologic record of the AVF indicate that previous eruptions have initiated with a phreatomagmatic phase, which can eventually transition into magmatic explosive style depending on external water supply and magma volume (Kereszturi et al. 2014). Relative proportions of volcanoes in the AVF with some evidence for phreatomagmatic, magmatic explosive, and/or magmatic effusive activity are 80%, 60%, and 52% respectively (Kereszturi et al. 2014). The eruption style plays an important role in the type of volcanic hazards that manifest during the eruption (Table 1.2). Areas affected by edifice formation from AVF eruptions are typically small (~1 km^2) but hazards such as pyroclastic density currents (up to 5-6 km from vent), lava flow (tens of kilometres from vent) and tephra fall (tens to hundreds of kilometres from vent) can travel considerable distances from the vent (Keresturi et al. 2014). Eruptions within the AVF can complexly transition between eruption styles and fluctuating activity, affecting the sequencing and types of hazards that occur (Houghton et al. 1999). Volcanic eruption sequences in the AVF have been characterised based on the number of eruption styles (phreatomagmatic, magmatic explosive, magmatic effusive) that occur during an eruption: single (any single eruption style), compound (an eruption with any two eruption styles), and complex (an eruption with all three eruption styles). AVF eruption volumes typically fall within the range of 0.001 – 0.1 km^3, but the most recent eruption (Rangitoto) is also the largest recorded eruption within the AVF at 1.1 km^3 (Figure 1.3).

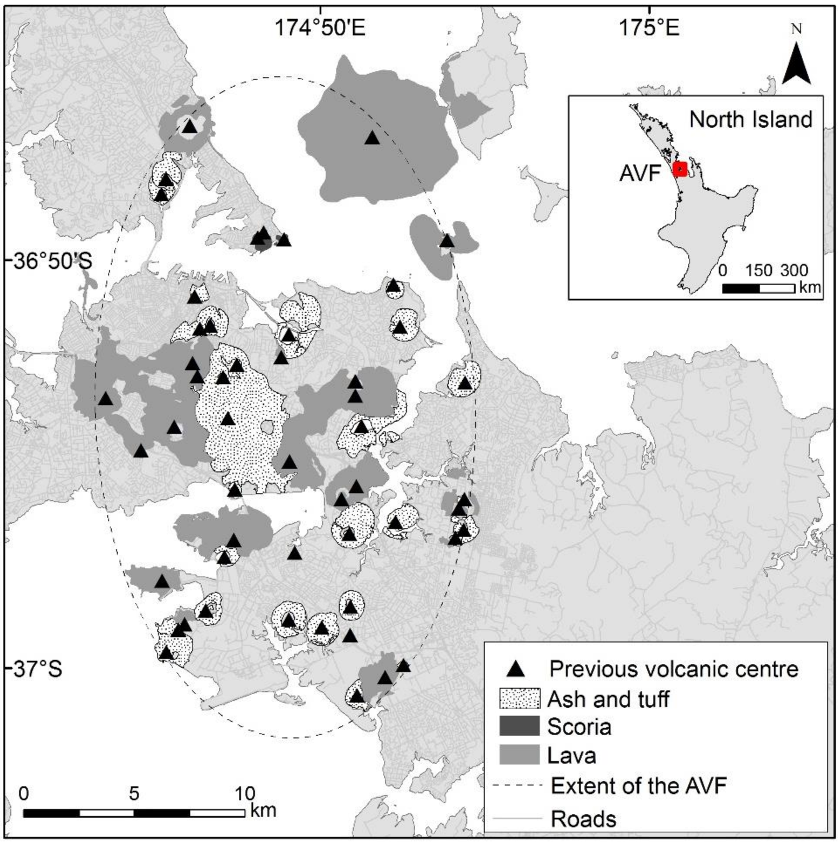

Figure 1.2: The extent and previous eruptive centres, and deposits of the AVF (extent from Runge et al. 2015).

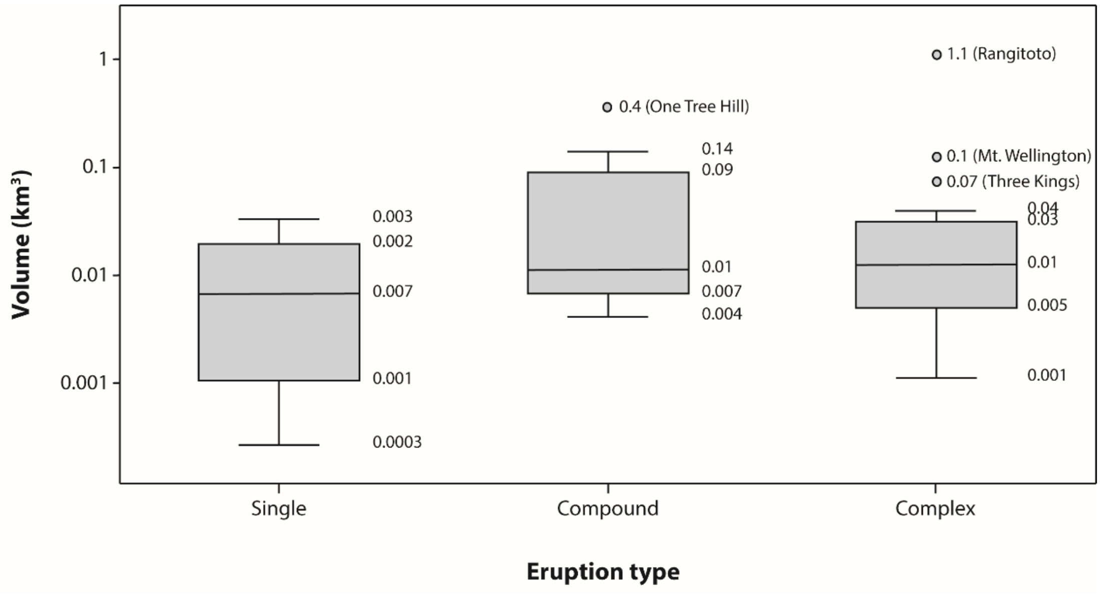

Figure 1.3: AVF bulk erupted volume (not including distal tephra) (Figure from Hayes et al. 2018 and adapted from Electronic Supplementary Material 2 of Kereszturi et al. 2013)

Table 1.2: Volcanic eruption hazards of the AVF as identified by previous studies and categorised by eruption style (Allen and Smith 1994; de Lange and Healy 2001; Magill and Blong 2005; Lindsay 2010; Hayward et al. 2011)

Volcanic hazard	Magmatic eruptions	Phreatomagmatic eruptions
Edifice formation	✓	✓
Explosion generated tsunami		✓
Fire-fountaining	✓	
Land deformation	✓	✓
Lava flow	✓	
Pyroclastic density current		✓
Scoria cone formation	✓	
Shockwave	✓	✓
Tephra fallout	✓	✓
Volcanic ballistic projectile	✓	✓
Volcanic gas emission	✓	✓

Tephra hazard from distal volcanoes

Central North Island volcanoes can also affect Auckland through the deposition of tephra fall (Figure 1.4; Sandiford et al. 2001, Shane and Hoverd 2002, Molloy et al. 2009, Zawalna-Geer et al. 2016). Central North Island andesitic stratovolcanoes (Taranaki, the Tongariro complex, Ruapehu and White Island) erupt on average every 50 to 300 years (Lindsay and Peace 2005). Eruptions are typically small to moderate-sized eruptive episodes over a long period of time (Wilson et al. 1995; Johnston and Becker 2001). Rhyolitic calderas (Taupo, Okataina, Rotorua and Mayor Island) erupt less frequently (approximately every 1,000 to 2,000 years) as moderate to large-sized eruptions and can generate large quantities of tephra (Wilson et al. 1995; Lindsay and Peace 2005). Tephra from these volcanoes can be dispersed and deposited hundreds of kilometres from the source. The thickness of tephra fall in Auckland from distal volcanoes will depend on wind directions and speeds, magnitude, duration of eruption(s), and eruption column height (Hurst and Smith 2010).

Several drill core sites in Auckland have revealed approximately 40 tephra layers that have been deposited over the past 27 ka originating from distal North Island volcanoes (Sandiford et al. 2001, Shane and Hoverd 2002, Molloy et al. 2009, Zawalna-Geer et al. 2016). The frequency of tephra falls in Auckland varies depending on the source, drilling location, and approach used to determine the tephra record (Table 1.3; Molloy et al. 2009; Zawalna-Greer et al. 2016). Based on cryptotephra and microtephra records, tephra falls from all sources (including the AVF) and of any thickness could reach Auckland at recurrence intervals of 0.4-0.6 ka (Zawalna-Greer et al. 2016). However, due to tephra preservation issues these estimates must be treated with caution as not all tephra falls will be preserved and not all tephra falls will reach areas that can be cored (e.g., lakes). A modern example is the observed light tephra fall from the 1995-96 eruption of Ruapehu, which was enough to cause the closure of Auckland International Airport on 18 June 1996, but not preservation of a macroscopic tephra layer (Johnston et al. 2000). Using an advection-diffusion model to simulate tephra fall from eruptions of Volcano Explosivity Index (VEI) 4 and higher from all terrestrial volcanoes within 500 km of Auckland eruptions Jenkins et al. (2018) calculate annual exceedance probabilities for tephra falls exceeding 1, 10, and 100 mm as 1.5×10^{-4}, 7.8×10^{-5}, and 3.4×10^{-5} respectively. Thus, tephra has been deposited in Auckland numerous times in the past and has the potential to do so again in the future, but there is substantial uncertainty associated with estimating the likelihood.

Table 1.3: Estimated frequency (ka) of tephra fall in Auckland (any thickness) from distal sources

Tephra source	Molloy et al. (2009)	Zawalna-Geer et al. (2016)
Taranaki	1.5	3.0-9.0
Okataina / Taupo	3.8	3.0 (Okataina) / 1.3-2.0 (Taupo)
Tongariro	11.4	2.2-4.4
Mayor Island	40	9.0

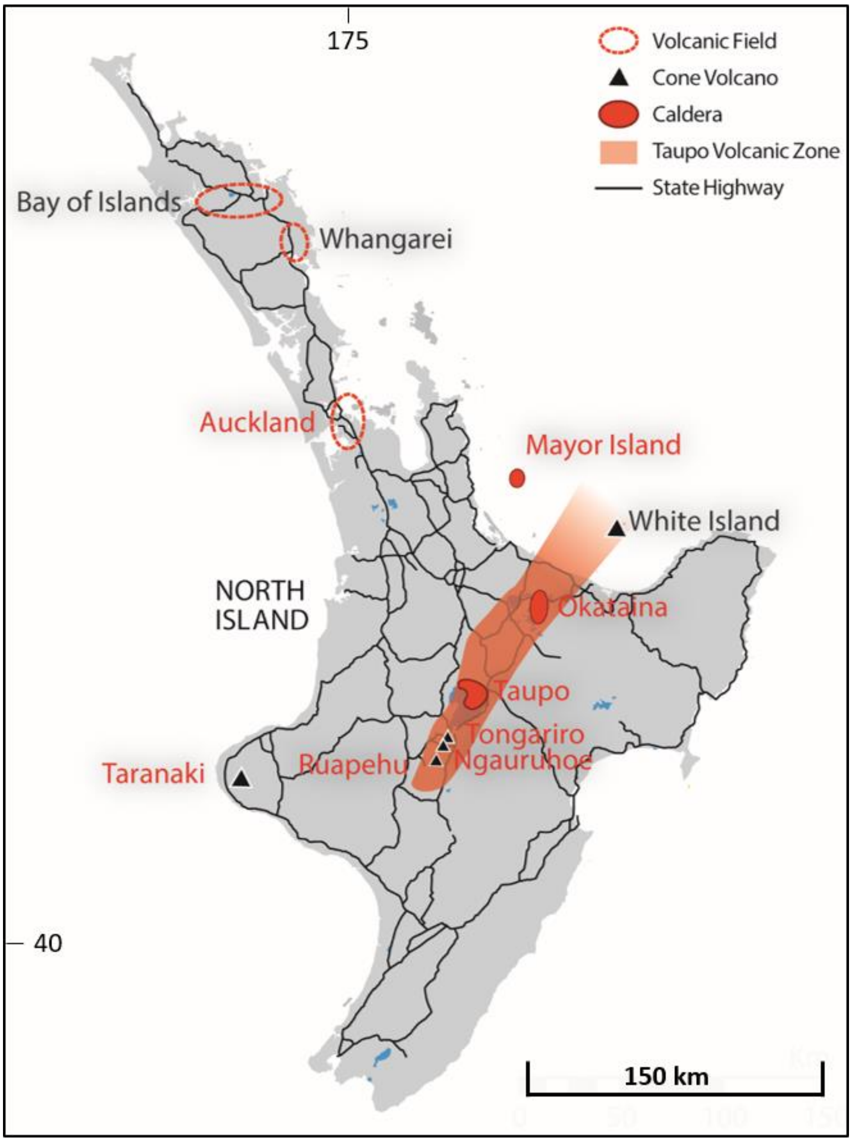

Figure 1.4: New Zealand volcanoes and potential future sources of distal tephra affecting Auckland. Note: red font used for sources evident within existing cores in Auckland.

A summary of volcanic risk management in Auckland

Due to population size and urban development in Auckland, it is not considered feasible to use land use planning as a hazard avoidance tool (Becker et al. 2010). Consequently, a large effort has been placed on contingency planning for a future AVF eruption by Auckland Emergency Management and lifelines (critical infrastructure) organisations. Recognition of the AVF as a potential threat to Auckland has been recognised and hazard characterisation has occurred for some time (Searle 1961; Searle 1964; Allen and Smith 1994). Systematic effort to understand the risk posed by the AVF began with the establishment of the Auckland Engineering Lifelines Project (AELP) in 1996 (Daly and Johnston 2015). The aim of AELP was to take an all hazards approach to investigate ways to assess and mitigate the potential damage to and disruption of utilities such as gas, power, water, and wastewater (Daly and Johnston 2015). As part of the project, a clear focus was on the risk posed by the AVF and so a suite of five local and two distal eruption scenarios were developed to explore the potential effects of a future AVF eruption on critical infrastructure (Johnston et al. 1997a, b). This formed the basis for early volcanic contingency planning in Auckland (Auckland Regional Council 2002).

Continuing the early work of the AELP, the Auckland Lifelines Group[1] (ALG) was established in 2000. ALG coordinates lifelines utilities input into CDEM activities and lifeline organisations are encouraged to participate in ALG as part of their obligations under the Civil Defence and Emergency Management Act (2002). Further recognition of the importance of volcanic risk in Auckland led to the establishment of the Volcanic Impacts Study Group as a sub-committee of the ALG in 2004 for the purpose of (VISG 2016):

- Collating and advocating existing knowledge about volcanic impacts on, and mitigation measures for, lifeline infrastructure.
- Facilitating and supporting research on the impacts of volcanic hazards on lifeline infrastructure and development of appropriate mitigation measures.

[1] Originally called Auckland Engineering Lifelines Group (AELG).

- Two-way exchange of relevant research between the research community and the lifeline infrastructure community.
- Facilitating reconnaissance investigations, and/or advocate lifeline representation on reconnaissance investigations, to active volcanic areas where this would add to knowledge about impacts on infrastructure.
- Providing a national focal point for volcanic impacts work on lifeline infrastructure.

VISG facilitates ongoing dialogue between the lifeline infrastructure and research communities by holding an annual forum, where representatives from each present about recent activities. Several research projects that VISG has investigated include: health and safety impacts of tephra (Lindsay and Peace 2005), tephra impacts on Auckland's water supply (Johnston et al. 2004), impacts on electricity, telecommunication and broadcasting networks (Wilson et al. 2009). In 2001, potential collection and disposal issues of tephra in Auckland was investigated (Johnston et al. 2001). This included identification of potential volumes and characteristics of ash likely to affect Auckland from a variety of volcanic sources. This study also investigated potential disposal issues, including characteristics of desirable disposal sites. However, the study did not consider wider disaster waste sources such as those generated from damaged buildings and infrastructure. The study estimated clean-up costs could amount to anywhere between NZ$2 million to NZ$100 million. Magill et al. (2006) also costs tephra clean-up in Auckland, but from an insurance perspective using a probabilistic loss model. Magill et al. (2006) found that clean-up losses could amount to NZ$50 million at annual return intervals of 600-3000 years to over NZ$450 million at an annual return interval of over 1 million years. More recently, VISG developed a suite of posters summarising advice to lifeline utilities managers about how to handle tephra (including urban clean-up) (Wilson et al. 2015), and updated posters were published in 2019.

In 2008, a National Emergency exercise called 'Exercise Rūaumoko' was held to test New Zealand's 'all-of-nation' measures for responding to an AVF eruption (Brundson and Park, 2009). The exercise focussed on the lead up to an eruption and stopped shortly after the eruption started (Brundson and Park, 2009). There was recognition that clean-up would be required, but no consideration of the potential scale of clean-up or the necessary resources to manage it (Ministry of Civil Defence and Emergency Management 2008). This scenario has since been developed into an educational simulation exercise (Dohaney et al. 2015; Fitzgerald et al. 2016) and used to access infrastructure outages (Deligne et al. 2015a; Deligne et al. 2017b; Blake et al. 2017) and building damage (Deligne et al. 2017a).

The Determining Volcanic Risk in Auckland (DEVORA) research and outreach programme was initiated in 2008, as a cooperative effort including GNS Science and New Zealand universities, which is sponsored by the New Zealand Earthquake Commission and Auckland Council (Deligne et al. 2015b). The aim of DEVORA is to provide a strategy and rationale for risk mitigation in Auckland through improved assessment of hazard and risk (Lindsay 2010; Deligne et al. 2015b). The DEVORA research programme achieves this by integrating three primary themes: Geological, probabilistic volcanic hazard, and risk and society (Deligne et al. 2015b). Government representatives sit on the DEVORA steering committee to help guide research directions and ensure that DEVORA outputs are useful (Deligne et al. 2015b). As part of DEVORA research, Hayes et al. (2017) built on the earlier work of Johnston et al (2001)by developing a refined model for assessing tephra clean-up in Auckland, which assessed potential volumes requiring removal, and the costs and durations of clean-up operations. Hayes et al. (2017) estimated costs of clean-up amounting to NZ$600 thousand for a thin distal scenario (1 mm thickness) to NZ$25 million for a thick distal scenario (10 mm). Local AVF eruption clean-up costs would amount to NZ$50 million for a moderate sized eruption to just under NZ$700 million for a large-scale eruption (Hayes et al. 2017). The duration of clean-up for thin distal tephra falls would be approximately one month, whilst for a thick distal scenario it would take approximately three months. For the local AVF eruptions, clean-up could be quickly conducted in some areas outside major damage areas (e.g., a few days to a week), but that areas nearer to the vent could potentially take years to remove the tephra. This study did not consider other potential waste streams.

Tephra clean-up is an acknowledged issue facing Auckland and a few studies have investigated the potential consequences. However, a considerable gap that must be filled is the exploration of more complex waste streams that could be generated due to the interaction between the variety of AVF volcanic hazards and Auckland built environment.

1.6 THESIS OBJECTIVES AND SCOPE

The overarching aim of this thesis is to improve understanding of clean-up and restoration of urban areas after volcanic eruptions. Auckland City, New Zealand, is used as a case study to investigate planning requirements, and numerous international case studies of volcanic eruptions are used to inform the analysis undertaken in this thesis.

This thesis is situated within Disaster Risk Reduction, specifically drawing from Disaster Waste Management and Disaster (with focus on Volcanic Hazard) Risk Assessment sub-disciplines. As such, it is important to clearly articulate the scope of this thesis. Disaster waste management is an emerging research field that has a wide body of potential issues that all require investigation. The intention of this thesis is to act as a starting point for investigating disaster waste issues associated with volcanic eruptions, and in particular develop assessment tools that can aid in identifying operational and strategic management planning requirements for further analysis. This thesis is not intended to investigate all aspects of disaster waste management for volcanic eruptions. For this reason, several important aspects of disaster waste management are not dealt with in detail, each of which require specific in-depth research. Detailed investigation is considered beyond the scope of this thesis for the following issues:

- Human health and safety risk management.
- Natural environment management.
- Disaster waste disposal.
- Disaster waste recycling.
- Sewage disaster waste management.
- Cultural considerations of disaster waste management.
- Municipal waste management.

To meet the stated aim and stay within the stated scope outlined above, the objectives of this thesis are to:

1. ***Build up an international evidence base for disaster waste clean-up after volcanic eruptions.***

   There is currently a lack of comprehensive analysis of disaster waste management requirements for the spectrum of volcanic hazards. This objective will involve compiling and analysing a range of international case studies to investigate the major challenges associated with disaster waste management following volcanic eruptions. A detailed case study of the 2015 eruption of Calbuco volcano, Chile, is also used throughout to explore post-eruption damage, disruption, and clean-up.

2. ***Develop and improve modelling techniques that can aid in the planning of post-eruption disaster waste clean-up requirements***

   There are two components of this objective. First, the 2015 eruption of Calbuco volcano, Chile, is used to test a tephra clean-up model using real world data from the Calbuco 2015 eruption. The second component is to develop a framework for quantifying and classifying waste produced from a range of volcanic hazards.

3. ***Develop a suite of volcanic eruption scenarios for the Auckland Volcanic Field (AVF) that consider a credible range of expected phenomena and can be used to quantify and characterise disaster waste clean-up from AVF eruptions.***

   This work will involve developing a suite of realistic eruption scenarios for the AVF that consider the temporal evolution of volcanic hazards during an eruption sequence (including unrest). These scenarios will be used as a test case for the disaster waste clean-up framework developed in objective two.

1.7 THESIS STRUCTURE AND DECLARATIONS

This PhD thesis is a coherent body of work investigating how disaster waste clean-up and management can be assessed to identify issues for contingency planning. The thesis first uses case studies to contextualise disaster waste management after volcanic eruptions, before focusing on demonstrating how planning considerations can be identified using scenarios and modelling for the study area of Auckland, New Zealand. The thesis contains numerous works published, in review, or prepared for submission to academic journals and scientific reports. I am the lead author of all chapters and the work contained within this thesis is my own. Numerous co-authors have made useful contributions, and these are declared in the signed co-authorship forms. Acknowledgements within each chapter are made to those that provided additional assistance.

The subsequent content of this thesis forms 5 core research chapters, and a conclusion chapter:

- Chapter 2 uses international case studies of disaster waste management following volcanic eruptions to identify knowledge gaps and place disaster waste management following volcanic eruptions into context. This work is intended to be submitted to the International Journal of Disaster Risk Reduction.
- Chapter 3 reports on the tephra clean-up experiences of four different communities in Chile and Argentina following the 2015 eruption of Calbuco volcano. The research also uses geospatial analysis to test the conceptual model developed from earlier work of Hayes et al. (2015) and Hayes et al. (2017) modelling tephra clean-up requirements after volcanic eruptions. This manuscript is in review with the Journal of Applied Volcanology. This work is a component of a larger research project investigating the impacts from the Calbuco eruption on Chilean infrastructure, utilities, agriculture, and health. The full findings of this impact assessment have been published as a GNS Science Report and can be found in Appendix A.
- Chapter 4, in another component of the Calbuco eruption impact assessment, details the damage to residential structures following the 2015 Calbuco eruption. It explores the many data quality issues associated with analysing empirical damage information following volcanic eruptions. This work has been published in the Journal of Volcanology and Geothermal Research.

- Chapter 5 summarises the interdisciplinary approach undertaken to develop a suite of multi-hazard eruption scenarios for the Auckland Volcanic Field. The scenarios are intended to be used for a variety of disaster risk reduction purposes, including exploring post-eruption clean-up and waste management requirements in this thesis. This work is intended for publication in the Journal of Volcanology and Geothermal Research. A GNS Science Report detailing the scenario development process, assumptions, and modelling approaches is presented in Appendix C.
- Chapter 6 develops an approach to characterising and quantifying the waste generated from volcanic eruptions and applies this approach to the Auckland Volcanic Field using the DEVORA scenarios from Chapter 5. This work is intended for publication within the Journal of Volcanology and Geothermal Research.
- The final chapter of this thesis (Chapter 7) concludes by summarising the key findings in relation to the thesis objectives. It recommends future research requirements to build upon the work contained within this thesis.

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Chapter 2: Volcanic Hazards and Disaster Waste Management

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ABSTRACT

A ubiquitous challenge of disaster response and recovery is managing disaster waste. Past disasters have demonstrated that these events can create enormous volumes of different types of waste, at times overwhelming existing solid waste management systems. Despite this, disaster waste management is rarely planned for prior to a disaster. Rarer still is the consideration of volcanic hazards in such planning. This omission is problematic as volcanic hazards can create very large volumes of disaster waste and create unique challenges that other natural hazards (e.g., earthquake, hurricane, flooding) do not exhibit, such as long (potentially multi-year) durations of waste accumulation and high uncertainty associated with when volcanic activity may cease. Here, we have contextualised waste management after volcanic eruptions by using case studies to explore the effects of waste generated by volcanic hazards on disaster waste management systems for the purpose of identifying important considerations for contingency planning. Our findings suggest that the spectrum of different hazards and their unique processes pose a considerable difficulty to managing waste after volcanic eruptions. Contingency planning will require identifying management requirements for the unique properties of some volcanic waste products (e.g., lava), large volumes of highly mixed waste streams, and long durations of volcanic activity with substantial uncertainty on the timing and end of waste generating events. Our work consolidates disparate information on disaster waste management after volcanic eruptions and so will be beneficial for risk-reduction, emergency response and recovery managers to understand clean-up and restoration requirements for areas affected by volcanism.

2.1 INTRODUCTION

Disaster waste management is a critical aspect of disaster response and recovery (Brown et al. 2010, 2011). During disaster response, authorities may need to rapidly manage debris that has trapped people inside buildings or is impeding important access routes for evacuation and emergency services (Lauritzen 1998). Slow and inefficient waste management processes can stall recovery efforts following major disasters (Swan 2000; Luther 2006). Pre-established plans for waste management improve the effectiveness and efficiency of clean-up operations (Crowley 2017). Despite disaster waste management being a critical component of post-disaster response and recovery, few localities have pre-established disaster waste management plans unless mandated through legislation (Brown et al. 2010, 2011; Crowley and Flachsbart 2018). A lack of prior planning can lead to sub-optimal disaster waste management practices that consequently hamper response and recovery efforts (Brown et al. 2011; Crowley 2017; Domingo and Luo 2017).

There has been an increase in the number of disaster waste management studies in the academic literature over the last decade, mostly focussed on earthquakes. Domingo and Luo (2017) used semi-structured interviews with governmental and non-governmental organisations to investigate earthquake construction and demolition waste management processes resulting from the 2011 Canterbury Earthquake Sequence. They found that a lack of waste-processing facilities, incomplete policies, organisational limitations, and poor communication and coordination were issues associated with managing earthquake construction and demolition waste. They recommended more complete pre-established waste management plans and more powerful legislation relating to disaster waste management is required in New Zealand. Shibata et al. (2012) presented on issues resulting from tsunami-generated waste resulting from the 2011 Great East Japan Earthquake, finding that radiation contamination made disposal difficult and caused delays in the disaster waste management process. They recommended that policies are required for dealing with cascading disasters. Kawamoto and Kim (2016) also investigated disaster waste management following the 2011 Great East Japan Earthquake, exploring issues of social capital and the effect on disaster waste management efficiency. They found that communities with high social capital conducted more efficient disaster waste management. Memon (2016) analysed disaster waste management following the 2015

Nepal Earthquake, and highlighted issues associated with collecting reliable disaster waste data in a post-disaster setting, and particularly in developing countries. Memon (2016) found that limited resources, difficult terrains, and changing government priorities can all contribute to challenging data collection. The above studies provide useful insights into potential issues associated with earthquake disaster waste, but more studies are necessary to investigate the diverse range of potential hazards that communities are exposed to.

Different hazardous events (e.g., earthquakes, floods, tsunami, volcanic eruption) can have considerable influence on the type and quantity of disaster waste generated and the required management approaches (Brown et al. 2011). Hazardous processes associated with volcanic activity can damage the built environment to such a degree that waste products are generated that require management to facilitate urban rehabilitation (Table 2.1). For example, Chaiten Town, Chile was inundated by lahars from the 2008 Chaiten eruption, which destroyed and buried buildings, vehicles, and infrastructure in up to 3 m of lahar deposits (Pierson et al. 2013). Studies exist that discuss the damage mechanisms of volcanic hazards on the built environment, which we refer the reader to for more in-depth discussion (Jenkins et al. 2014; Wilson et al. 2014).

Highly destructive volcanic hazards that deposit volcanic products (e.g., PDC and lahar) can generate highly mixed waste products including construction and demolition debris, household waste products, electronics, vegetation, biological, and eruptive products. To date there has been little consideration of the challenges associated with managing these potentially complex disaster waste streams. Further, many existing disaster waste management guidelines have either no or limited consideration of the waste management requirements for volcanic eruptions (e.g., UN OCHA 2011; US EPA 2019). This is problematic as there are presently over 800 million people worldwide living within 100 km of an active volcano (within range for tephra fall) and 29 million people living within just 10 km (within range of multiple highly destructive volcanic hazards) (Figure 2.1; Brown et al. 2015). Thus, understanding disaster waste management in the context of volcanism is a necessary component of disaster risk reduction and developing robust and flexible disaster waste management plans (UNISDR 2015).

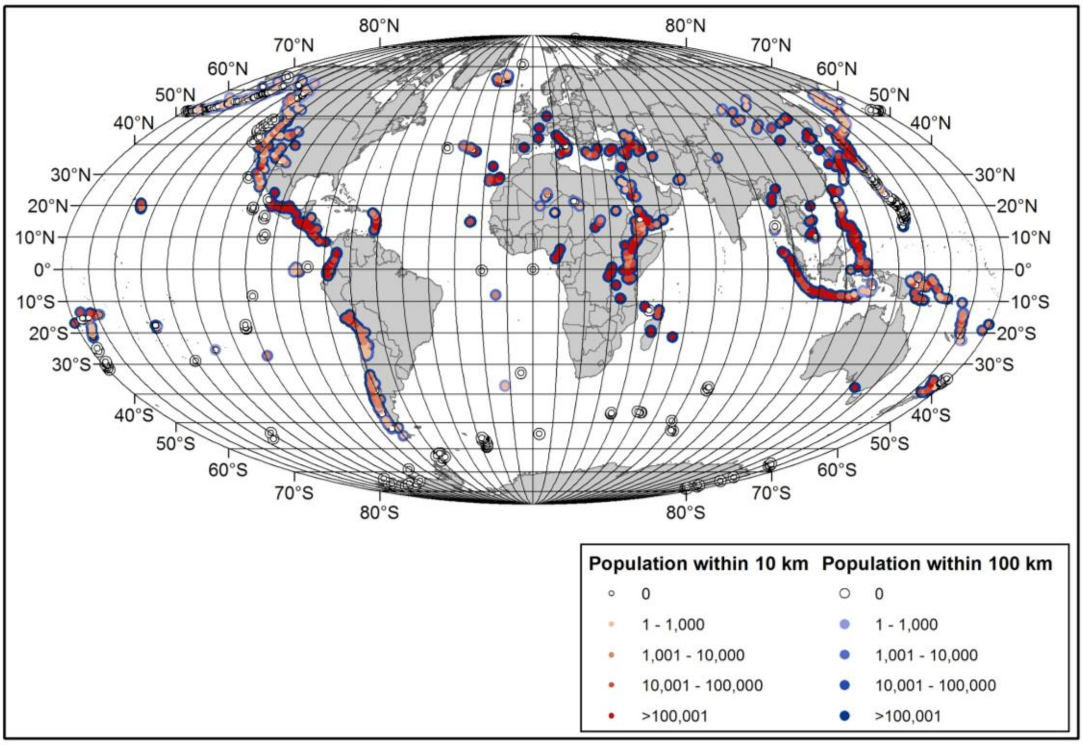

Figure 2.1: Global distribution of population exposure to volcanoes active in the Holocene (Based on Volcano Population Exposure Index (Brown et al. 2015). Data from https://data.humdata.org/dataset/volcano-population-exposure-index-gvm)

In this contribution, we present an overview of the impact volcanic hazards can have on disaster waste management systems. Specifically, we explore 1) the characteristics of disaster waste generated by volcanic eruptions, such as the type, quantity and duration of accumulation, 2) specific challenges volcanic hazards present to disaster waste management systems, and 3) gaps that exist in the academic literature relating to disaster waste management following volcanic eruptions. We use case studies to review disaster waste characteristics from a variety of different disasters associated with volcanic activity. In section 2.2, we provide an overview of criteria used to select case studies and our approach to analysing case studies. In section 2.3, we present an overview of the selected case studies. In section 2.4, we present the findings from our analysis, then in section 2.5, we discuss the disaster waste management challenges and considerations for contingency planning associated with volcanic activity. In section 2.6, we discuss the limitations of our analysis, and future research requirements.

Table 2.1: Summary of damage and disruption mechanisms from volcanic hazards

Volcanic hazard	Typical damage mechanism(s)	Example reference(s)
Tephra fall	• Deposition of tephra deposit causing functionality loss of societal assets • Damage to buildings by static loading, ingress, or corrosion	Spence et al. (1996); Blong (2003); Wilson et al. (2012), Wilson et al. (2014); Hayes et al. (2015, 2019a)
Volcanic gas	• Corrosion of building contents and metal objects	Blong (1984); Kling et al. (1987)
Lava bombs / volcanic ballistic projectiles	• Building damage through perforation of building • Fires from heat of projectile	Blong (1984)
Lahars	• Deposition of mud, silt, and boulders causing functionality loss of societal assets • Damage to built environment though dynamic forces, and water and sediment ingress • Transportation of waste (e.g., buildings, vegetation) from upper reaches of river	Blong (1984; Baxter (1990); Wilson et al. (2014); Jenkins et al. (2015); Hayes et al. (2019a)
Lava flows	• Lava emplacement • Damage to building though dynamic forces • Fires from heat of lava flow • Damage from explosions generated from gas build up or water interaction	Blong (1984); Wilson et al. (2014); Jenkins et al. (2017)
Pyroclastic density currents	• Deposition of pyroclastic volcanic products • Building damage from dynamic pressure and fires	Baxter (1990); Baxter et al. (2005); Jenkins et al. (2013)
Shockwaves	• Windows breaking	Blong (1984); Magill et al. (2013)
Volcanic vents / fissures	• Complete damage of any built structure	Hirose and Tajika (2000)
Deformation	• Building and infrastructure damage	Hirose and Tajika (2000)
Earthquakes	• Building damage from ground shaking	Blong (1984)
Volcanically induced tsunami	• Building damage from dynamic forces, and water ingress • Sediment deposition • Transportation of debris	Blong (1984)

2.2 METHODS

Most of the attention of disaster waste management for volcanic eruptions has focussed on the operational aspects of municipal tephra clean-up operations (Hayes et al. 2015). Here, we attempt to develop a more holistic representation of disaster waste management from volcanic eruptions. The purpose of this is to outline the interactions between volcanic hazards and disaster waste management, outline the challenges associated with disaster waste management after volcanic eruptions, and identify knowledge gaps to guide future research. We use case studies to explore these issues.

Case study analysis is important for disaster research as it facilitates learning important lessons and contributes to the academic body of knowledge (Taylor 1978; Burton 2010; Grynszpan et al. 2011). Various methodological approaches can be utilised, such as explanatory, exploratory, multiple, and collective case study analysis (Rowley 2002; Yin 2003; Baxter and Jack 2008; Stake 2013). A common facet from all approaches is that there tends to be no set number of case-studies required to analyse a particular issue of concern, rather it depends on the complexity of the topic, the diversity of appropriate case-studies, and (critically) the richness of the available case studies for analysis – both in terms of what occurred and what has been recorded (Yin 2003; Baxter and Jack 2008; Stake 2013). That said, typically the number of case studies should amount to fewer than 15 so the analysis does not become too convoluted (Miles et al. 1994). When selecting case studies for this paper we put emphasis on selecting a diverse range of case studies that had enough data recorded for appropriate analysis. However, a limitation is the lack of detailed case studies in the disaster waste management field in general (Brown et al. 2011), let alone for volcanic eruption related DWM.

Due to limited reporting of volcanic disaster waste issues in the literature, detailed analysis of some topics falls outside the scope of this work:

- Human health and safety risk management.
- Natural environment management.
- Management of commercial/industrial material
- Disaster waste disposal.
- Disaster waste recycling.

- Sewage disaster waste management.
- Cultural considerations of disaster waste management.
- Municipal waste management.

2.2.1 Case study selection

A mixed-method approach to compile a list of situations where disaster waste activity in a community (generally with an urban focus) occurred due to a volcanic eruption. A literature search using google scholar was undertaken first. Grey literature and unpublished field notes collected by the New Zealand volcanic impact research group during impact reconnaissance trips (Wilson et al 2010) were also investigated. The Em-Dat database (global database containing over 22,000 disasters: https://www.emdat.be/) was explored for potential case studies. Finally, informal discussions with other volcanic disaster risk and resilience researchers through my own and supervisor's professional networks were used to identify additional case studies for consideration. Case studies at this initial stage were limited to those occurring since 1950 to ensure that case studies would still be of most relevance in the modern environment (e.g. availability of heavy machinery, environmental standards). The next step was to assess whether each case study had the necessary information for further analysis. This required identifying specific details of the community affected (e.g. location, name, whether it is a city/village/town), volcanic hazard(s) that occurred, a quantitative estimation/measurement of volcanic products that affected the community, estimates of number of fatalities (if they occurred), damage data, and waste management information. Damage data was classified based on information quality and comprehensiveness of observations (e.g. "approximately 200 buildings damaged", "all buildings destroyed", compared with a detailed damage assessment was undertaken e.g. Blong 2003).

2.2.2 Case study analysis

Cross-case analysis is a method of inquiry that facilitates the comparison of commonalities and differences in events, activities, and processes (Miles et al. 1994; Khan and VanWynsberghe 2008; Stake 2013). It allows the researcher(s) to determine conditions that different findings occur within and form general categories for how those conditions are related (Stake 2013). Thus, cross-case analysis is an ideal method to fulfil this study's aims.

To explore the interactions between volcanic hazards and disaster waste management we investigate the types and quantity of waste generated and the duration that waste generation occurs over. We then use this information to inform analysis of waste management requirements and difficulties from volcanic eruptions for the purpose of informing volcanic contingency planning.

Identifying waste streams

Waste generated from disasters is a function of the characteristics of the hazardous process(es) and the type of asset(s) exposed (Brown et al. 2011). To identify waste streams in each of our case studies, we used published written descriptions and photographs of the volcanic deposits, types of volcanic hazards, and damage to characterise typical disaster waste streams (Table 2.2). Construction and demolition waste are typically characterised as parts of damaged buildings and infrastructure (e.g., roads, bridges, pipe networks, power lines) and is the most commonly characterised waste stream after disasters (Brown et al. 2011). When buildings are damaged or contaminated, electronics and white goods within the buildings can be damaged and require removal and appropriate disposal (Brown et al. 2011; Tabata et al. 2016; Leader et al. 2018). When industrial areas are affected by a disaster it is possible that industrial chemicals may require careful and specialised management to remove and dispose of appropriately (Brown et al. 2011). The Great East Japan Earthquake also demonstrated potential issues that could arise due to nuclear facilities being damaged due to disasters (UNEP 2012). Household hazardous waste can be challenging to manage, especially when large numbers of houses are condemned, and teams must systematically check each house before demolition can begin (Austin 2012; Waghorn et al. 2012). Putrescent waste is generated when food is left to rot due to long-lasting evacuations or power outages (Brown et al. 2011). Animal carcasses have also been included within this category (Brown et al. 2011). Hazards with high forces can fell trees and strip vegetation, which can further damage infrastructure and buildings or block rivers. Vehicles can be damaged or contaminated by disasters, meaning that they are a complete loss and require recycling of parts where possible and careful disposal (Brown et al. 2011). Unconsolidated sediment or rocks can be generated and require management following disasters often requiring heavy earth-moving machinery and care in case deposits pose a risk to human health (e.g., liquefaction ejecta mixed with sewage) (Brown et al. 2011; Villemure et al. 2012; Hayes et al 2015).

Detailed reporting of disaster impacts from volcanic eruptions has until very recently been rare, which means that it is likely that some waste products may have been generated but have not been reported publicly. To avoid over-speculation, we have only considered the waste streams that have been reported in the literature and have not included waste that logically may have been generated (e.g., household contents as a result of building collapse). This is a limitation but will also provide insights into the limited data reporting of this important information.

Table 2.2: Typical waste streams from disasters

Waste stream	Examples of potential constituents of the waste stream
Construction and demolition	Damaged buildings, roads, pipe networks, power lines.
Electronics and white goods	Refrigeration, television sets, computers.
Hazardous waste	Radioactive material, industrial chemicals
Household hazardous waste	Refrigerant, oils, pesticides, paints.
Putrescent	Spoiled food, animal corpses
Vegetative	Downed trees.
Vehicles	Cars, boats, helicopters, airplanes
Unconsolidated sediment or rocks	Tephra, mud, silt, sand.

Characterising disaster waste quantity

Obtaining an understanding of how the quantity of disaster waste streams influences management requirements is an important aspect of contingency planning as it allows identification of management requirements under future potential disaster scenarios (USEPA 2008). However, obtaining consistent, reliable, and useful measures of post-disaster waste quantity for comparison is a considerable challenge for several reasons. Post-disaster reporting of disaster waste quantities are rarely consistent. For example, some studies report waste as a volume (e.g., cubic metres or cubic yards), others will report disaster waste as mass (e.g., kilograms or tonnes) and due to varying waste compositions, it is not simple to convert between them (Brown et al. 2011). There is inconsistency in the types of disaster waste that are reported as some studies will cite estimates of the total waste generated, whilst others will report just building debris and often these distinctions are unclear. Likewise, the geographical area of reference can be ambiguous, and estimates can be an aggregate of regional or national disaster waste, which is problematic if local estimates are required. It is rare that the method of waste quantification is documented, and estimates are usually presented at face value (Brown et al. 2011). For example, estimates can come from order-of-magnitude approximations from municipal authorities, detailed waste logging at disposal facilities, numbers of truck loads, estimates from geospatial analysis and aerial imagery, or rule-of-thumb estimates (Brown et al. 2011). There is also little in the way of distinguishing the quantity of waste generated, and the quantity of waste that was disposed or treated. This distinction is poorly made in the literature but is important to consider because not all waste will be treated in the same manner and not all waste necessarily requires removal from where it rests post-disaster. All the above issues point towards relatively poor data quality in the international literature, which is a problem that appears to exist for all types of disaster and considerably limits the insights that can be obtained from the information.

Problems with quantifying waste from volcanic eruptions relate to a disconnect between field based physical volcanology studies undertaken during or after a volcanic eruption and the clean-up requirements on the ground. For example, in the literature tephra is often reported as an average thickness or loading (e.g., isopach or isomass maps) and estimates of volume are usually provided as either a bulk eruptive volume for an entire eruption or eruptive phase that may affect hundreds or thousands of square kilometres, or as a dense rock equivalent (DRE), all with varying degrees of uncertainty (Pyle 2015). However, data requirements from a disaster waste management perspective are most typically related to the volume (or mass) of tephra in a specific area of interest, such as a town or city. Therefore, assumptions are required relating to the geographical extent of the affected area and deposit bulk density to obtain estimates of volume of tephra in an area of interest (Hayes et al. 2015; Hayes et al in review). Total volume or mass is also not necessarily the most informative measure because the same volume/mass of material geographically spread over a wide area will have different management requirements to the same volume/mass in a concentrated geographical area (Hayes et al. 2015). Hayes et al. (2015) developed a framework that linked tephra accumulation (measured as volume per unit area of hazard exposure) to the likely clean-up response required on a four-degree semi-quantitative scale (very low: < 500 m^3/km^2; low: 500-10,000 m^3/km^2; medium: 10,000-50,000 m^3/km^2; high: >50,000 m^3/km^2). Thus, we used the same scale to characterise the quantity of tephra deposits in each of the case studies used in this work. To characterise accumulation, we used published thickness or loading information. If a range of thickness was provided by the source material (e.g., 5-10 cm) we used the middle value (e.g., 7.5 cm). Where possible we used published deposit bulk density measurements, and where none were published, we used a standard bulk density of 1200 kg/m^2. When considering the range of accumulation used within each level of the tephra clean-up scale, we assume minor variations in thickness and bulk density are unlikely to unduly influence the resulting classification.

We have been unable to source any publicly available estimates of disaster waste generated from the built environment for volcanic eruptions. One option in lieu of this is to use rules-of-thumb to obtain estimates of building debris generated based on damage information (FEMA 2010). However, there are some data quality issues associated with damage information from volcanic eruptions that require consideration. For example, detailed damage information has rarely been published after volcanic eruptions, and just a handful of studies have conducted comprehensive analysis of post-eruption damage (e.g., Spence et al. 1996; Blong 2003; Baxter et al. 2005; Jenkins et al. 2013; Jenkins et al. 2015; Jenkins et al. 2017; Hayes et al. 2019a: Chapter 4). Damage information can be subjected to ambiguities in the asset typology classifications and detailed engineering level measurements (e.g., floor area, height) can be elusive (Jenkins et al. 2015; Hayes et al. 2019a: Chapter 4). This is problematic because debris generated from different building types could substantially influence final total quantity of waste generated. Detailed quantitative information relating to damage of other built environment assets that could generate waste (e.g., damaged sewer lines, destroyed bridges) is also limited (Wilson et al. 2014). Therefore, it is difficult to obtain accurate and reliable quantitative estimates of post-eruption waste generation for the built environment. Thus, we use a semi-quantitative scale to classify built environment waste generation as either low, medium, high or very high based on descriptions from the literature on the number of damaged or destroyed buildings or qualitative descriptions (Table 2.3). If there was ambiguity between or within sources, we used a range to describe the waste quantity (e.g., low to medium, medium to high).

We acknowledge that using the total number of damaged buildings means that it is not possible to draw conclusions about the relative capacity of the community to respond. For example, a small rural community that has to clean-up debris from 100 destroyed buildings may have less resources available than if a large metropolitan area had to conduct the same clean-up. However, other factors may also influence the relative coping capacity (e.g., high-income country compared to low-income country). Our intention is to characterise the quantity of waste generated, regardless of the coping capacity of the affected community.

Table 2.3: Classification schema for characterising disaster waste quantity in the built environment

Built environment quantity classification	Number of damaged buildings	Examples of qualitative information used to assign built environment waste classification
Low	1-10	"A few buildings damaged"
Medium	10-100	"Dozens of damaged buildings" "tens of destroyed buildings'
High	100-1000	"Hundreds" "many" "large number of buildings destroyed"
Very high	>1000	"Most buildings damaged or destroyed" "whole town/city destroyed" "catastrophic damage"

Duration of waste accumulation

The duration of volcanic eruptions spans several orders of magnitude from several seconds to well in excess of a year (Jenkins et al. 2007; Pyle 2015). Unrest associated with volcanism (e.g., seismicity, land deformation, gas) can also occur before, during, and after volcanic eruptions (Sparks et al. 2012). The effects of volcanic eruptions can also lead to substantial landscape response (e.g., erosion, aggradation) for decades after volcanic eruptions (Major et al. 2000; Gran et al. 2011). Given the potential long duration of volcanic unrest, eruptions, and their effects, it is useful to contextualise the duration with how long waste was accumulating for before, during, or after the eruption. Instances of multiple "shocks" such as repeated tephra fall deposition with periods of quiescence in between have been noted as influencing tephra clean-up operations as there is reluctance to begin cleaning until the eruption has finished (Hayes et al. 2015). Given a long duration eruption it may be possible and desirable to clean-up in between sporadic waste accumulation events (e.g., tephra fall), so we also indicate whether the waste accumulation was consistent through time or sporadic. Our aim is to broadly characterise, rather than precisely define, hence waste accumulation timeframes are described as short (1 - 7 days), intermediate (7 - 30 days), long (30 - 365 days), and very long (>365 days).

2.3 SELECTED CASE STUDIES

Results from our case study selection is presented in Table 2.4. There is a considerable number of tephra fall case studies, which means that not all were selected in this study. Hayes et al. (2015) also conducted an in-depth review of tephra clean-up operations. Thus, case studies that only had tephra fall hazard were selected based on different areas of the world being affected and to obtain a variety of tephra accumulations. Five case studies were selected as they provided useful insights for areas affected by multiple hazards:

- Eldfell – Heimaey, Iceland (1973).
- Unzen-Fugendake – Shimabara, Japan (1990).
- Tarvurvur and Vulcan – Rabaul Town, Papua New Guinea (1994).
- Usu – Abutu, Japan (2000).
- Pacaya – Guatemala City, Guatemala (2010).

Despite data limitations, both Nevado del Ruiz – Armero, Columbia (1985) and Pinatubo – Bacolor, Philippines (1991) were included because no other case studies contained so many fatalities.

For this study we have selected 13 case studies for analysis, a summary of each is contained in Table 2.5.

Table 2.4: Case study selection criteria

Eruption – Location (Start year)	Hazard	Volcanic product data	Fatality data	Damage data	Waste management data	Selected: Yes (✓), No (X)
Sakurajima – Kagoshima, Japan (1955-present)	Tephra fall.	Yes	N/A	Not reported	Yes	✓
Agung – Villages in Bali (1963)	PDC.	No	Yes	Descriptive	Not reported	X
Eldfell – Heimaey, Iceland (1973)	Tephra fall, ballistics, lava flow, new vent formation, and volcanic gases.	Yes	Yes	Descriptive	Yes	✓
Semeru - Sumber Wullah Village, Indonesia (1976)	Lahar.	No	Not reported	Descriptive	Not reported	X
Usu - Sobetsu Spa, Japan (1977)	Land deformation and earthquakes, and tephra fall.	Yes	Not reported	Descriptive	Not reported	X
Usu - Toyako Spa, Japan (1977)	Land deformation and earthquakes, and tephra fall.	Yes	Not reported	Descriptive	Not reported	X
St. Helens – Spokane, USA (1980)	Tephra fall.	Yes	N/A	Not reported	Yes	X
St. Helens – Moscow, USA (1980)	Tephra fall.	Yes	N/A	Not reported	Yes	X
St. Helens – Moses Lake, USA (1980)	Tephra fall.	Yes	N/A	Not reported	Yes	X
St. Helens – Ritzville, USA (1980)	Tephra fall.	Yes	N/A	Not reported	Yes	X

St. Helens – Yakima, USA (1980)	Tephra fall.	Yes	N/A	Not reported	Yes	✓
St. Helens – Portland, USA (1980)	Tephra fall.	Yes	N/A	Not reported	Yes	✓
Nevado del Ruiz – Armero, Columbia (1985)	Lahar.	Yes	N/A	Descriptive	Not reported	✓
Pinatubo – Bacolor, Philippines (1991)	Lahar.	Yes	Yes	Descriptive	Not reported	✓
Hudson – Chile Chico, Chile (1991)	Tephra fall.	Yes	N/A	Not reported	Yes	X
Hudson – Los Antigos, Chile (1991)	Tephra fall.	Yes	N/A	Not reported	Yes	X
Unzen-Fugendake – Shimabara, Japan (1990)	Lahar, PDC, and tephra fall.	Yes	Yes	Descriptive	Yes	✓
Spurr – Anchorage, USA (1992)	Tephra fall.	Yes	N/A	Not reported	Yes	X
Tarvurvur and Vulcan – Rabaul Town, Papua New Guinea (1994)	Lahar/floods, tephra fall, and tsunami.	Yes	Yes	Detailed	Yes	✓
Soufrière Hills – Plymouth, Montserrat (1995)	PDC	Yes	Yes	Descriptive	No	X
Usu – Abutu, Japan (2000)	Land deformation and earthquakes, lahar, and tephra fall.	Yes	N/A	Descriptive	Not reported	✓
Etna – Catainia, Italy (2002)	Tephra fall.	Yes	N/A	Not reported	Yes	X

Reventado – Quito, Ecuador (2001)	Tephra fall.	Yes	N/A	Not reported	Yes	X
Chaiten – Chaiten Town, Chile (2008)	Lahar.	No	N/A	Descriptive	Not reported	X
Chaiten, Futaleufu, Chile (2008)	Tephra fall.	Yes	N/A	Not reported	Not reported	X
Pacaya – Guatemala City, Guatemala (2010)	Tephra fall and storm.	Yes	N/A	Not reported	Yes	✓
Shinmoedake – Miyakonojo, Japan (2011)	Tephra fall.	Yes	N/A	Descriptive	Yes	✓
Cordon-Caulle – Villa La Angostura (2011)	Tephra fall and lahar.	Yes	Yes	Descriptive	Yes	✓
Cordon-Caulle – Bariloche (2011)	Tephra fall.	Yes	N/A	Not reported	Yes	X
Fogo - Chã das Caldeiras (2014)	Lava flow.	No	N/A	Detailed	Not reported	X
Calbuco – Ensenada (2015)	Tephra fall and lahar.	Yes	N/A	Detailed	Yes	✓

Table 2.5: Summary of case studies

Location (volcano – damage/disruption occurred start/end years(s))	Eruption start date / end date (GVP 2013)	Volcanic Hazard(s)	Summary of impacts	References used
Kagoshima, Japan (Sakurajima - 1955 to present)	13 October 1955 / 22 August 2016	Tephra fall	Semi-regular small accumulation tephra falls across parts of the city causing transportation disruption and public health issues.	Yano et al. (1990); Durand et al. (2001); Ishihara (2007); Hayes et al. (2015)
Heimaey, Iceland (Eldfell - 1973)	23 January 1973 / 28 June 1973	Tephra fall, ballistics, lava flow, new vent formation, volcanic gases	Rapid evacuation of 5000 inhabitants in a short time window. Substantial damage to ~400 buildings and deposition of volcanic products within town.	Thorarinsson et al. (1973); Williams and Moore (1983); Morgan (2000)
Yakima, USA (St. Helens - 1980)	20 March 1980 / 28 October 1986 (± 3 days)	Tephra fall	Moderate accumulation of tephra affecting city. Considerable disruption to transportation and commerce. Damage to waste water treatment plant.	Blong (1984)
Portland, USA (St. Helens - 1980)			Low accumulation of tephra affecting city. Minor impacts to transportation.	Markesino (1980); Blong (1984)
Amero, Columbia (Nevado del Ruiz - 1985)	11 September 1985 / 13 July 1991	Lahar	Lahar destroyed entire town and killed approximately 21,000 people.	Gueri and Perez (1986); Voight (1990); Mileti et al. (1991)
Bacolor, Philippines (Pinatubo - 1991)	2 April 1991 / 2 September 1991	Lahar	Lahars occurred during monsoon season for years following the eruption. Deaths from these lahars could amount to as high as 1000. Most buildings were destroyed by 1995. Officials called for town to be abandoned by this was opposed by some within the community refusing to leave.	(Crittenden (2001); Rodolfo and Crittenden (2002); Crittenden and Rodolfo (2003); Crittenden et al. (2003)
Shimabara City, Japan (Unzen-Fugendake eruption - 1990 to 1995)	17 November 1990 / 16 February 1995 (± 15 days)	Lahar, PDC, tephra fall	Evacuation required in some parts of the city due to hazard from PDC and lahar. Over 2511 buildings destroyed. Sporadic low accumulation tephra falls affected ground transportation.	Kobayashi et al. (1993); Ohta (1997); Takahashi and Fujii (1997); Nakada et al. (1999); Taketsugu et al. (2004); Unzen-Fugendake Eruption Disaster Study Group (2007); Ikeya (2008); Cooper (2018)

Rabaul Town, Papua New Guinea (Tarvurvur and Vulcan - 1994)	19 September 1994 / 16 April 1995	Lahar/floods, tephra fall, tsunami	Required evacuation. Hundreds of buildings damaged and destroyed, by tephra fall, mudfills, lahars, and tsunami. Some damage to buildings and contents from looting. Many roads only passable by 4WD vehicles. Power lines damaged by tephra fall, erosion, and flash flooding.	Blong and McKee (1995); Dent et al. (1995); Rabaul Government (1995a, b); Blong 2003)
Abutu town, Japan (Usu - 2000)	31 March 2000 / 15 September 2001 (± 5 days)	Land deformation and earthquakes, lahar, tephra fall	Required evacuation of population. Roads damaged by faults and large blocks ejected from volcano and blocked by tephra deposition. Sewerage line damaged by faults. Buildings damaged by surface deformation tilting.	Hirose and Tajika (2000); Tiwari et al. (2001) Hiramatsu et al. (2002); Jones (2016)
Guatemala City, Guatemala (Pacaya - 2010)	9 March 2006 / 26 October 2010	Tephra fall	Moderate accumulation of tephra fall. Coincided with a major cyclone.	Wardman et al. (2012)
Miyakonojo City, Japan (Shinmoedake - 2011)	19 January 2011 / 7 September 2011	Tephra fall	Moderate accumulation of tephra in a large urban centre.	Magill et al. (2013)
Villa La Angostura, Argentina (Cordon-Caulle - 2011)	4 June 2011 / ~21 April 2012	Tephra fall, lahar	High accumulation of tephra in a relatively small town. Sixteen houses collapsed and 40 required bracing to prevent collapse from tephra fall.	Craig et al. (2016); Elissondo et al. (2016); Forte et al. (2018); Wilson et al. (2013)
Ensenada, Chile (Calbuco - 2015)	22 April 2015 / 26 May 2015	Tephra fall, lahar	High accumulation of tephra in a small spread out village. Evacuation required. Damage to 307 buildings from tephra fall. Considerable aggredation of riverbeds. Roads blocked by thick tephra deposition.	Hayes et al (2019a,b,c)

2.4 CHARACTERISTICS OF WASTE GENERATED BY VOLCANIC HAZARDS

2.4.1 Reported waste streams and waste quantity

Volcanic products

Some of the waste streams generated from volcanic activity are the natural products produced by the eruption. These include deposits from tephra fall, pyroclastic density currents (PDCs), lahars, and lava. Each of these types of volcanic products have required clean-up and management of some form in the case studies used in this paper. All the case studies' waste streams included tephra fall, PDC deposits, or lahar deposits in some form (Table 2.6). However, the quantity spans several orders of magnitude from trace amounts (e.g., Kagoshima City, Japan) to several metres in thickness (e.g., Amero, Columbia). The quantity can also exhibit substantial spatial variation within affected communities. For example, deposits in Shimabara City, Japan were several metres thick in areas affected by PDCs, but only a few g/m^2 in areas affected by tephra fall (Takahashi and Fujii 1997).

Built environment waste

Depending on volcanic hazard typology and intensity, the built environment waste generated also varies in type and quantity (Table 2.6). Tephra falls usually require substantial accumulations before waste from engineered structures will be generated (Table 2.6). The case study of Ensenada, Chile, is particularly notable for the wide variety of hazard intensity (0.5 mm to 55 cm), causing a general grading of waste generation from minor roof cover replacement to complete collapse of some buildings exposed to over 10 cm (Hayes et al. 2019a: Chapter 4). Lahars are generally characterised by their potential for large quantities of waste generation (Table 2.6). Near complete destruction of Armero, Colombia, occurred as a result of a lahar generated from the Nevado del Ruiz eruption of 1985. In the business district, only the remnants of foundations remained because the lahar sheared off the upper part of all structures at the building foundation (Mileti et al. 1991). Despite the destruction, little debris was observed by those conducting post-disaster reconnaissance throughout the city as most of it had been transported (by the force of the lahar) several kilometres to the southeast or deeply buried within the deposit (Mileti et al. 1991). The emergence of new volcanic vents is highly destructive to structures that are in close proximity (Williams and Moore 1983; Hirose and Tajika 2000). Considerable deformation can occur (> 1 m: Tiwari et al. 2001) and material ejected from the volcano (e.g., ballistic projectiles) can be highly damaging (Williams and Moore 1983; Hirose and Tajika 2000). One of the clearest examples of this is the 2000 eruption of Usu, Japan. The damage resulting from the 2000 eruption was mostly limited to areas within 1 km of the vent, but damage was extensive in this area after ~50 new vents emerged over the course of the eruption (Hirose and Tajika 2000). As a result of the 2000 eruption, houses and schools were relocated outside of areas considered highly hazardous. Much of the building debris remains in situ as the area has been developed into a disaster geopark to serve an educational function (Ishikawa 2013; Jones 2016).

Putrescent waste

Putrescent waste was reported in four of the case studies. The Calbuco 2015 eruption resulted in an evacuation and exclusion zone being placed on a 20 km area around the volcano, that remained in place for one month before it was reduced to 10 km (Hayes et al. 2019b: Appendix A). This resulted in putrescent waste being produced and there was concern from Chilean public health officials about these wastes left inside the cordon causing an infestation of vermin and outbreaks of hantavirus pulmonary syndrome (Hayes et al. 2019b: Appendix A). In Rabaul Town, food spoilage occurred due to power failure and contamination from a tsunami that affected a food storage facility (Blong and McKee 1995).

Human remains

Human remains often have specific handling requirements including maintaining dignity for the dead and ensuring that appropriate evidence is collected for coroner investigations (Morgan et al. 2006; Leditschke et al. 2011; Wagner 2014; Cordner and Ellingham 2017), which must be done prior to management of other wastes. Human fatalities occurred in six case studies (Heimaey, Amero, Bacolor, Shimabara City, Rabaul, and Villa La Angostura). In Heimaey, one death occurred as a result of exposure to toxic volcanic gases (Williams and Moore 1993). In Rabaul Town, four fatalities occurred but how they died is ambiguous (Blong and McKee 1995). In Villa la Angostura a child was killed playing on a pile of tephra that was close to high tension power lines (Wilson et al. 2013). The remaining case studies where human fatalities occurred were mass fatality events (defined as ≥10 deaths per event: Kim et al. 2013; Wilson et al. 2017). In Amero and Bacolor a substantial number of people died (over 21,000 and 1,000 respectively), and many were buried within thick volcanic deposits, making recovery of remains challenging (Gueri and Perez 1986; Voight 1990; Crittenden 2001; Rodolfo and Crittenden 2002). There has been no reporting on the specific management requirements in each of these case studies for dealing with human remains, but this is likely to be dependent on the cultural norms of the affected people and planning is required within the local context (Gupta 2016).

Mixed waste streams

Several case studies (Heimaey, Amero, Bacolor, Shimabara City, Rabaul Town, Abata Town, Villa la Angostura, and Ensenada) had instances of multiple waste streams co-located (e.g., tephra fall deposits and construction and demolition: Table 2.6). In Amero, Columbia and Bacolor, Philippines, mass fatalities occurred where substantial areas of the built environment were entirely buried by sediment from lahars, which overtime hardened and encased buildings (Mileti et al. 1991; Crittenden 2001: Figure 2.2A). Rabaul Town was affected by considerable quantities of highly mixed waste in the form of tephra deposits, mud, vehicles, construction and demolition waste, vegetative debris, and putrescent waste all co-located (Figure 2.2B). Heimaey had complex waste mixing due to substantial volumes of tephra fall deposits, lava, and building debris (some fire damaged) (Figure 2.2C-E). Fires also gutted buildings as a result of PDCs generated during the Unzen-Fugendake eruption (Ikeya 2008).

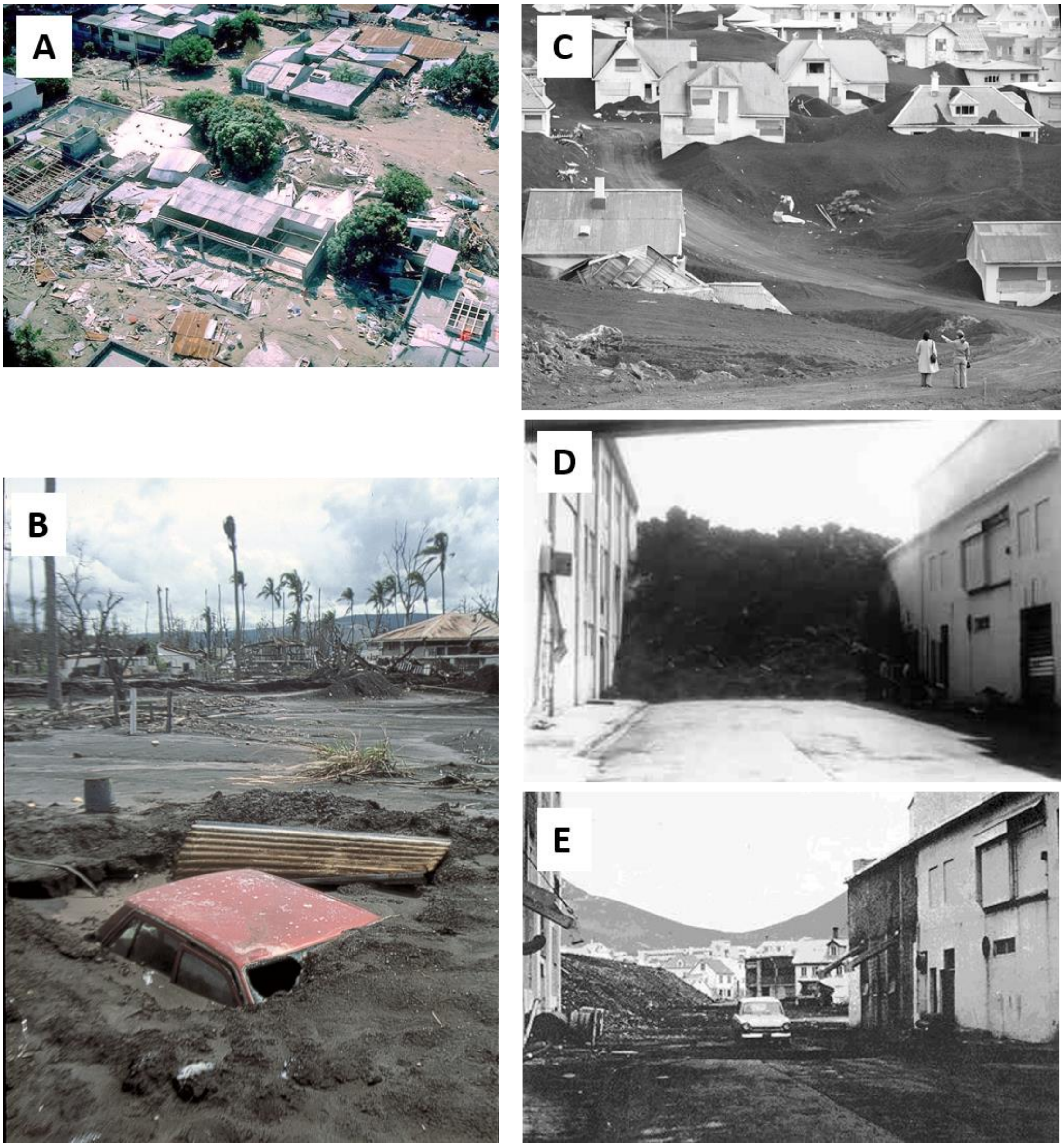

Figure 2.2: Examples of post-eruption environments in selected case studies. A) Armero, Columbia (photo credit: U.S. Geological Survey/photo by N. Banks. Public domain), B) Rabaul Town, Papua New Guinea (Photo credit: AusAid. Public domain), C) Houses affected by tephra fall on Heimaey, Iceland (Photo credit: Christian Bickel. CC BY-SA 2.0), D) Lava flow blocking street in Heimaey, Iceland (Photo credit: U.S. Geological Survey/photo by Richard S. Williams. Public domain), E) Lava flow partially removed from street (Photo credit: U.S. Geological Survey. Public domain).

Table 2.6: Comparison of the hazardous processes, waste streams and waste quantity

Case study	**Mass fatality event?**	**Evacuations?**	**Volcanic hazard**	**Confirmed disaster waste streams**	**Tephra / sediment quantity**	**Built environme nt waste quantity**
Kagoshima, Japan (Sakurajima - 1955)	No	N/A	Tephra fall	-Tephra fall deposits	Very low - low	None reported
Heimaey, Iceland (Eldfell - 1973)	No, but one person died from breathin g in the volcanic gases.	Yes – 6 months. However, 200-300 volunteers remained to prevent damage from the eruption	Tephra fall	-Tephra fall deposits -Construction and demolition waste	High	Medium
			Lava flow	-Lava -Construction and demolition	N/A	High
			Gas	-Construction and demolition	N/A	Low-Medium
Yakima, USA (St. Helens - 1980)	No	No	Tephra fall	-Tephra fall deposits	Moderate	None reported
Portland, USA (St. Helens - 1980)	No	No	Tephra fall	-Tephra fall deposits	Low	None reported
Amero, Columbia (Nevado del Ruiz - 1985)	Yes, over 21,000 attribute d to lahar	Permanently abandoned	Lahar	-Construction and demolition -lahar deposit -putrescent waste	High	Very high
Bacolor, Philippines (Pinatubo - 1991)	Yes – over 1,000 attribute d to lahar	Partial abandonment, a few hundred people refused orders to leave	Lahar	-Construction and demolition -lahar deposit -putrescent	High	Very high
Shimabara City, Japan (Unzen-Fugendake - 1990)	Yes, 43 died attribute d to PDC.	Partial evacuations of hazardous areas	Lahar	-Lahar deposit -Construction and demolition -vegetation	High	Very high
			Tephra fall	-Tephra fall deposits	Very low to low	None reported

			Pyroclastic density current	-Pyroclastic density current deposits -Construction and demolition	High	High
Rabaul Town, Papua New Guinea (Tarvurvur and Vulcan - 1994)	No, but four separate deaths occurred in the town during the eruption	Yes	Tephra fall	-Tephra fall deposit -Construction and demolition -Vehicles	High	High
			Lahar	-Lahar deposit -Construction and demolition	High	Moderate to high
			Tsunami	-Tsunami deposit -Construction and demolition -Putrescent	Unquantified	Medium
Abuta town, Japan (Usu - 2000)	No	Yes	Land deformation and earthquakes	-Construction and demolition	N/A	High
			Lahars	-Lahar deposit -Construction and demolition	High	High
			Tephra fall	-Tephra fall deposits	Moderate	Low
Guatemala City, Guatemala (Pacaya - 2010)	No	No	Tephra fall	-Tephra fall deposits	Moderate	None reported
Miyakonojo City, Japan (Shinmoedake - 2011)	No	No	Tephra fall	-Tephra fall deposits	Moderate	None reported
Villa La Angostura, Argentina (Cordon-Caulle - 2011)	No, but one child died at a tephra disposal site.	No	Tephra fall	-Tephra fall deposit -Construction and demolition	High	Medium
			Lahar	-Lahar deposit -Vegetation -Construction and demolition	Unclear	None reported
Ensenada, Chile	No	Yes – 1 month.	Tephra fall	-Tephra fall deposits	Low to high	High

(Calbuco - 2015)		However, restricted access was available after a couple days for clean-up and damage assessments.		-Construction and demolition -Putrescent		
			Lahar	-Lahar deposit -Construction and demolition	High	Low

2.4.2 Duration of waste accumulation

Determining how long an eruption will last is a considerable area of uncertainty relating to volcanic activity (Jenkins et al. 2007; Bebbington and Jenkins 2019). In the case studies, the duration of waste accumulation spans a wide range (a day to multiple years) (Table 2.7). The waste accumulation came in the form of both sporadic multiple shocks and continuous accumulation. The eruption at Heimaey included considerable tephra accumulation mostly over the first week (0.3 - 5 m thickness accumulated in the town), when the eruption rate was in excess of 100 m^3 s^{-1}, after the first week it slowed to 80 m^3 s^{-1} and after approximately six weeks reduced to ~10 m^3 s^{-1} and continued reducing for the remainder of the eruption's duration (Thorarinsson et al. 1973; Williams and Moore 1983). In other case studies such as Kagoshima City, Japan, tephra deposition has been sporadic usually in small quantities but fluctuates depending on the volcanic activity (Durand et al. 2001). Monitoring data of activity at Sakurajima from 1956-2013 indicates that 11,828 explosions have been recorded, with repose periods between explosions lasting from 1 minute to 308 days (Jenkins et al. in press). The number of explosions per month (when an explosion does occur) varies considerably from hundreds during high activity phases to as low as just one or two (Iguchi et al. 2013; Tameguri and Iguchi 2019).

Damage to the built environment can accumulate through time as an eruption progresses. For example, the number of damaged buildings caused by the Unzen-Fugendake eruption accumulated through multiple PDC and lahar events over the course of several years and substantial damage was not recorded until over one year into the eruption (Ikeya 2008). Lahars affected Bacolor, Philippines, for several years after the 1991 Pinatubo eruption, with most houses destroyed by 1995. The ongoing lahar activity meant that the residents that remained in the city (approximately 11 % of the pre-eruption population: Rodolfo and Crittendon 2002) had to periodically raise their houses (on stilts) or build on top of houses as the ground level increased through each lahar event (Crittendon and Rodolfo 2002; Crittendon 2001). In addition to city-wide damage accumulation, damage to an individual building can accumulate through an eruption. This was experienced in Heimaey, Iceland, where tephra accumulated throughout the first week of the eruption on the roofs of buildings gradually increasing the loading force exerted (Thorarinsson et al. 1973; Williams and Moore 1983; Morgan 2000). In Rabaul Town, Papua New Guinea, multiple tephra falls and subsequent rainfall led to roof collapse of some buildings several weeks following the eruption onset (Blong and McKee 1995; Blong 2003). Thus, buildings may at first sustain minor damage (e.g., gutter collapse), which through time either through the effects of the eruption or other forces becomes more substantial. The sequencing of waste accumulation can be an important consideration as well. For example, collapsed buildings from earthquake shaking and land deformation in the early phases of volcanic activity were then buried by tephra deposits from the Usu 2000 eruption (Tiwari et al. 2001). Thus, pre- syn- and post-event sequencing and duration are important considerations when investigating disaster waste management requirements for volcanic eruptions.

Table 2.7: Characteristics of temporal accumulation of waste. Multiple shocks and continuous refer to waste generation events.

Case study	Waste type	Multiple shocks	Continuous	Duration
Kagoshima, Japan (Sakurajima - 1952 to present)	Tephra deposits	X		Very long
Heimaey, Iceland (Eldfell - 1973)	Tephra deposits		X	Short - intermediate
	Lava		X	Long
	Construction and demolition		X	Long
Yakima, USA (St. Helens - 1980)	Tephra		X	Short
Portland, USA (St. Helens - 1980)	Tephra		X	Short
Amero, Columbia (Nevado del Ruiz - 1985)	Lahar deposits		X	Short
	Construction and demolition		X	Short
Bacolor, Philippines (Pinatubo - 1991)	Sediment	X		Very long
	Construction and demolition	X		Very long
Shimabara City, Japan (Unzen-Fugendake eruption - 1990 to 1995)	Tephra / PDC deposits	X		Very long
	Lahar deposits	X		Very long
	Construction and demolition	X		Very long
Rabaul Town, Papua New Guinea (Tarvurvur and Vulcan - 1994)	Tephra deposits	X		Long
	Lahar deposits	X		Long
	Construction and demolition	X		Long
Abatu town, Japan (Usu - 2000)	Construction and demolition	X		Long
	Tephra deposits	X		Long
	Lahar deposits	X		Long

Guatemala City, Guatemala (Pacaya - 2010)	Tephra deposits	X		Short
Miyakonojo City, Japan (Shinmoedake - 2011)	Tephra deposits	X		Short
Villa La Angostura, Argentina (Cordon-Caulle - 2011)	Tephra deposits	X		Short
	Lahar deposits	X		Very long
Ensenada, Chile (Calbuco - 2015)	Tephra deposits	X		Short
	Lahar deposits	X		Very long
	Construction and demolition	X		Intermediate

2.5 MANAGEMENT CHALLENGES AND CONSIDERATIONS FOR CONTINGENCY PLANNING

According to disaster waste management literature, the type of waste, quantity of waste, degree of mixing, human/environmental health hazards, community priorities, funding mechanisms, and regulations all influence the feasibility and appropriateness of different waste treatment strategies (e.g., collection, separation, recycling, disposal) (Lauritzen 1998; Hayes et al. 2015; Brown and Milke 2016; Gabrielli et al. 2018). Here, we focus our discussion on how the type of waste, quantity of waste, degree of mixing, and duration of volcanic event can influence waste management strategies, including pre-event mitigation and post-event response and recovery. We do not discuss community priorities, funding mechanisms, and regulations as these are likely to vary by location irrespective of exposure to volcanic hazards.

2.5.1 Volcanic products and handling requirements

Tephra fall deposits

Tephra fall deposits are like other fine-grained sediment that may be deposited from other hazards such as floods, tsunami, or liquefaction, but there are a few specific characteristics that warrant consideration.

Tephra fall deposits are one of the most common products cleaned up following volcanic eruptions. This is because they can be transported and deposited hundreds of kilometres from the eruption source and so have the potential to affect many different communities. Therefore, it is not unusual that multiple communities will be affected by fall deposits during a single eruption, as seen with the examples of Portland and Yakima both being affected by the Mount St. Helens eruption (but at different times through the eruption sequence). It is also noteworthy that the characteristics of the tephra fall deposits (chemistry, mineral content, grainsize, mechanical strength, deposit bulk density, thickness) can differ markedly with distance from the eruption source, between discrete explosions within an eruption sequence, across different eruption sequences, across different volcanoes, and with climate, and these differences in characteristics require different management strategies (Hayes et al. 2015). The characteristic that will influence the management strategy the most is the thickness of the deposit (Hayes et al. 2015). Thin deposits (e.g., trace amounts up a few millimetres) are typically managed through increased road maintenance with road sweeper trucks (e.g., Kagoshima, Japan) and households can usually self-manage clean-up without the need for substantial assistance from authorities. However, as the thickness increases it will become more efficient for authorities to provide removal assistance to manage congestion at local dump sites and limit poor or illegal disposal methods (Hayes et al. 2015). Heavy earth-moving machinery is also necessary to improve the efficiency of removal operations. Disposal options will be dependent on the volume that requires removal and engineering and environmental characteristics (e.g., leachable element concentrations, shear strength, porosity) (Hayes et al. 2015). Even modest thicknesses can result in substantial volumes to remove in large urban areas (Hayes et al. 2015; 2017). Grainsize and climate have been shown to influence the necessity for remobilisation suppression actions (Hayes et al. 2015). Semi-arid and arid environments have experienced difficulties with clean-up due to persistent remobilisation of the tephra (Hayes et al. 2015; Wilson et al. 2012; 2011; Forte et al. 2018). Potential disposal options and reuse as an engineered fill will depend on the material properties of the deposit (e.g., mechanical strength, chemistry, grainsize, bulk density). Some communities have explored reusing tephra fall deposits for a variety of purposes such as concrete and engineered fill (Shorey et al. 1983; Contrafatto 2017; Siddique 2012), but no comprehensive guidelines currently exist.

Pyroclastic density current (PDC) deposits

Pyroclastic density current deposits can be a challenging aspect of disaster waste management because: 1) they can be deposited in substantial volumes, 2) some deposits can remain hot enough to melt materials for days after it is emplaced, and 3) can result in highly mixed waste streams. The volumes can require large scale public works programmes to manage. If areas affected by PDC deposits are to be cleaned up, they will require heavy earth-moving machinery to clear deposits from roads and properties due to the relatively high accumulations. After initial emergency response, disaster waste management requirements are likely to rely upon decisions made about the future viability of restoring the affected area. This is because these areas may be subjected to increased or better characterised risk associated changes to the landscape or ongoing volcanic activity.

Lahar deposits

Lahars have the potential to deposit large quantities of sediment within affected communities or river catchments. Lahars can occur either syn-eruption or post-eruption (e.g., triggered by rainfall). It will be necessary to identify the potential changes to the sediment budget of affected catchments to determine the long-term management requirements. These requirements could vary from: 1) removal of sediment from river beds (e.g., Ensenada) to 2) development of large sediment retention dams (e.g., sabo dams at Unzen-Fugendake) to 3) abandonment of settlements in extreme cases (e.g., Armero). Options 1 and 2 will require considerable thought towards appropriate sediment disposal locations. Considerations required include sites that can cope with the expected quantity of sediment and whether they are environmentally appropriate, as deposits could be contaminated with sewage, petrol, oil, paint, cleaners, and industrial chemicals (Kelman and Spence 2004).

Lava

The temperatures of lava flows can range from ~750^{o}C to over 1200^{o}C (both extreme endmembers), far exceeding the ignition temperatures of cloth, paper and wood (Blong 1984). Although the crust of a lava flow can cool relatively quickly the interior of a lava flow can take weeks to decades to cool down. Lava inundation often results in communities at least temporarily abandoning the inundated land (Murton and Shimabukuro 1974; Williams and Moore 1983; Luhr et al. 1993). However, on rare occasions some benefits have been derived from lava flows inundated habited areas, such as extracting heat from lava flows to warm houses (Williams and Moore 1983). Given that land abandonment is a common consequence of lava flow inundation, attempts with varying degrees of success have be made in the past to divert lava flows to prevent them from infiltrating habitable land (Lockwood and Torgerson 1980; Moore 1982; Abersten 1984; Barberi et al. 2003). Roads and communities have been re-established by rebuilding on top of the lava flow once it has cool sufficiently (Chirico et al. 2009), but this is challenging for thick a'a' and blocky lava flows. However, a'a' and blocky flows will generally advance at a slower rate than pahoehoe, which may allow time to formulate options to mitigate damage such as moving assets or removing potentially hazardous elements such as fuel tanks (Williams and Moore 1983). Thus, from a disaster waste management perspective the options appear to be: 1) removing assets from within the likely pathway (either through long-term land use planning: (Sagala 2009) or rapid removal syn-eruption: (Gregg et al. 2004; Chester et al. 2012), 2) attempting to control where the lava flows, 3) quarrying the lava deposit for construction material after it has cooled sufficiently (and potentially disposing of encased waste materials), or 4) building on top of the lava once sufficiently cooled.

2.5.2 Interaction between volcanic products and built environment

Generated waste streams from disasters can be voluminous, wide in variety, and there is a high potential for mixed waste streams (Hachimura et al. 2009; Brown et al. 2011; Saffarzadeh et al. 2017). Identification of strategies for managing highly mixed waste streams will be necessary as part of robust disaster waste management planning for volcanic eruptions. This appears to be particularly true of volcanic flow hazards (e.g., lahar, PDC, lava flow) due to their potential to cause destruction. Mixed waste streams make recycling of materials difficult due to contamination and labour-intensive efforts required to separate waste (Brown and Milke 2016). Wastes may be contaminated with potentially hazardous materials that require careful and specialised treatment. Distinguishing clean fill waste from other waste streams that require more extensive management will be required.

In some jurisdictions waste ownership can be important to determine as waste can be transported across property or political boundaries (Brown et al. 2011). This is important because demolition contractors may have salvage rights to material on the site they are demolishing, but some material on site might not be owned by the property owner that has hired the contractor (Brown et al. 2011). Insurance implications can occur where material may be salvageable and removed from insurance pay-outs (Brown et al. 2011). The forces of lahars and PDCs are likely to transport waste across boundaries. Problematically, areas affected by these hazards are often evacuated prior to or following these hazards, meaning it might be difficult to obtain waste ownerships agreements due to absentee owners. Protocols for assigning waste ownership will need to be considered when developing plans for disaster waste management after volcanic eruptions.

Radical changes to the landscape that can occur from volcanic eruptions (e.g., vegetation stripping, deposition of large volumes of unconsolidated sediment) can cause long-term changes to the sediment budget of catchments, potentially increasing the probability of future waste generating events (e.g., further lahars, flooding). The long-term nature of these hazards and associated uncertainty can make it challenging to make long-term decisions about the viability of existing developments. This has led to some communities facing challenging decisions to balance the livelihoods of different communities and/or community members. For example, Bacor, Philippines, was initially designated by authorities as a sacrificial area and public works programs would direct lahars away from other areas and into Bacor, which was a major source of conflict with those in the community (Rodolfo and Crittenden 2002; Cooper 2018). This can mean that restoring these communities is delayed whilst these issues are resolved (potentially through litigation). Disaster waste management activities must be planned and carried out within this wider community context. Clear community engagement post-disaster in these circumstances will be necessary to reach outcomes that are palatable for all parties.

2.5.3 Health and safety hazards

The health and safety of the public and workers assigned to clean-up activities is an important consideration for all disaster waste management operations. Specific considerations for volcanic hazards include 1) hazards posed by the generated waste, and 2) hazards posed by volcanic activity or long-lasting environmental hazards.

The waste generated by volcanic eruptions can represent a health and safety risk for the population and workers that are required to manage it. For example, fires can occur during disasters due to damage to electrical appliances (e.g., Scawthorn 1986) and lava flows and PDCs have led to buildings and contents catching fire during volcanic eruptions (e.g., Heimaey and Shimabara City). Fires can release hazardous pollutants (chemical and particulate) and the burning of Polyvinyl chloride (used in wiring, construction materials, and other industrial applications) can release known human carcinogens (Bird and Grossman 2011). Thus, clean-up of fire damaged areas will require special consideration towards health and safety for clean-up workers.

The potential health impacts of tephra have been documented in a number of studies (e.g., Howell and Baxter 2006; Damby et al. 2013). Fine ash (PM2.5 and PM10) can be a health hazard due to skin, eye, and respiratory irritations and exacerbate existing conditions such as asthma (Horwell and Baxter 2006). Respirable crystalline silica within tephra can cause concern about the potential for chronic lung disease (silicosis), but there is currently no medical evidence of this occurring in volcanic settings (Horwell and Baxter 2006). Tephra deposits vary widely in the characteristics that can make them a health hazard (particle size distribution, silica content, and particle surface reactivity), and so analysis is required to assess the health hazard it may impose (Horwell and Baxter 2006; Le Blond et al. 2010; Horwell et al. 2013; Stewart et al. 2016). Similar assessments may be required of lahar and PDC deposits (Damby et al. 2013). Municipalities at high risk of tephra fall should investigate the costs and benefits of stockpiling the necessary personal protection equipment that their workers or the public may require in the event of a tephra fall. Tephra fall deposits are often cleaned by volunteers and property owners, so appropriate advice will need to be disseminated relating to (Hayes et al. 2015):

- Potential for slips, trips and falls;
- Potential health implications relating to tephra exposure;
- Correct personal protection equipment that should be worn;
- Correct lifting practices;
- Safety requirements if heavy earth-moving machinery are operating nearby.

Major public works programmes may be required to mitigate risks posed to communities from on-going volcanic activity. However, areas where these works are required may be located in high hazard areas. Hazard assessments will be a key information source used by disaster waste managers following a volcanic eruption to ensure that workers are safe from the effects of an eruption. Unmanned remote controlled hydraulic excavators, bulldozers, and wheeled dump trucks were used to construct sabo dams at Unzen-Fugendake and used to clear deposits at Usu to protect workers (Chayama et al. 2014; Tiwari et al. 2001). However, these were operated from a distance of only 100 m (Nagatani 2014), so emergency evacuation routes, buses on standby, protection shelters, and careful monitoring of volcanic activity were required.

2.5.4 Duration

The temporal dimension of volcanic hazards is perhaps one of the more challenging management aspects when associated with disaster waste management. As demonstrated through several of the case studies, volcanic eruptions can be relatively long duration events (compared to earthquakes and hurricanes for instance), and it is not simple to identify when an eruption has finished or when some hazardous phenomena (e.g., lahars) will cease. The relatively high uncertainty associated with when an eruption will cease or when destructive hazards associated with an eruption will abate makes it a challenge to determine when clean-up should begin and consequently when operations should transition from an emergency response phase to a recovery phase. The long duration of an eruption can lead to reluctance from community leaders and/or insurance providers to conduct permanent recovery activities (Sword-Daniels et al. 2014). This makes it difficult for authorities to determine when to begin large scale public works and community restoration projects.

2.6 LIMITATIONS AND FUTURE RESEARCH REQUIREMENTS

Volcanic eruptions can come in a variety of styles and sizes. When hazards intersect with society heterogeneous and dynamic vulnerability means the effects from volcanic eruptions are highly variable. Although we have tried to present a varied selection of case studies, our analysis is limited by the relatively small selection of relatively high-profile case studies analysed. This is due to limited reporting and analysis of disaster waste management conducted following volcanic events in the international literature. Detailed case studies that report and investigate across the spectrum of disaster waste management issues would be of considerable value to investigating some of the gaps in this analysis. Particular attention towards clean-up and recovery activities associated with proximal areas where multiple eruptive hazards may interact is a clear research area requiring attention.

The relative proportions of waste generated from volcanic eruptions is not well reported, especially for waste products that are not volcanic in nature. This is perhaps symptomatic of limited empirical datasets of damage to the built environment following volcanic eruptions. If there is limited quantification of what was damaged by the eruption, then limited quantification of the waste that was consequently generated and managed will also be limited. Limited empirical datasets are a well-documented issue in volcanic risk assessment globally (Wilson et al. 2012, 2014; Jenkins et al. 2014). Thus, continued development of post-eruption impact assessments is necessary.

Quantifying and characterising the potential solid waste generation for potential future disasters is an important aspect of contingency planning. Frameworks that quantify and classify disaster waste are useful of forward planning and forecasting waste that may need to be managed following disaster. Empirical and conceptual approaches have been developed for perils such as earthquakes, hurricanes, and floods (Chen et al. 2007; FEMA 2013; Brown 2014; García-Torres et al. 2017). For volcanic eruptions conceptual and empirically informed approaches have been used to quantify the amount of deposited tephra fall requiring removal (Hayes et al. 2017, 2019; Johnston et al. 1997; Magill et al. 2006; Zuccaro et al. 2013; Biass et al. 2017). However, the disparate and inconsistent reporting on the waste generated after volcanic eruptions to date makes the process of empirically quantifying and characterising other forms of solid waste (e.g., construction and demolition debris) challenging. We suggest that developing an approach conceptually and then testing the approach with future eruptions and refining as necessary may be the best way forward. Such an approach has already been taken to quantify tephra fall clean-up volumes for tephra falls (Hayes et al. 2015, 2017, 2019).

The management requirements associated with disposal of volcanic waste products from urban areas are not well understood. For example, geotechnical requirements of sending volcanic deposits to landfill (and potentially developing on top of them) must be investigated to ensure that slope instability issues do not manifest and require long-term management. Research that investigates how disposal sites can be evaluated and selected under different conditions (e.g., types of tephra, volumes of material, degrees of contamination) is needed.

Due to the large quantities of waste that can be generated by disasters, waste minimisation strategies are important to reduce required landfill space and incineration of waste. Waste minimisation through reuse or recycling of waste products can also reduce demand on raw materials post-disaster and potentially increase post-disaster job opportunities. The use of products produced by volcanic eruptions has occurred throughout human history (e.g., Marra et al. 2011; Pappalardo et al. 2017). However, there has only been limited research on the reuse of volcanic products from a post-disaster context, where they might be contaminated by other waste products (Contrafatto 2017). Feasibility studies that investigate the technical and logistical requirements of reusing volcanic products such as tephra that have been cleaned up from urban areas would be of value to the international literature. Design of rapid assessment frameworks based on simple and easily identifiable and measurable indicators that can allow for the triaging of waste that might have reuse potential (to undergo more detailed investigations) from waste that has no reuse potential and can be sent for immediate disposal would be of considerable use.

2.7 CONCLUSIONS

The issues associated with disaster waste management requirements after volcanic eruptions is a gap in the literature in the area of disaster response and recovery. This study has provided an overview of the issues relating to disaster waste management in the context of volcanic hazards using a case study analysis. Evidence from the case studies used in this work indicate that disaster waste management after volcanic eruptions is complex and can be context dependent. The variety and complexity of volcanic hazards and societal contexts included in this study suggests that there is no general common process to managing the disaster waste produced by volcanic eruptions. However, by characterising specific waste management issues that are unique to volcanic hazards such as the on-going and uncertain nature of volcanic events and the high degree waste mixing it will be possible to use existing frameworks for disaster waste management to plan for and manage disaster waste clean-up after volcanic eruptions.

For effective contingency planning it is necessary to understand the specific volcanic hazards likely to manifest during future eruptive activity, their likely hazard intensity, and how they will interact with the built (e.g., fragility of buildings to collapse) and natural environment (potential sediment control issues). For planning purposes, the use of hypothetical scenarios may provide a useful avenue for exploring potential disaster waste management issues a community may encounter.

Through the development of this work is was clear that there has been very little specific and detailed documentation of the disaster waste streams, quantities, and management requirements following volcanic eruptions. We highly recommend future forensic studies and impact assessments consider these issues as disaster waste management is a fundamental aspect of disaster response and recovery.

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Chapter 3: Tephra Clean-up After the 2015 Eruption of Calbuco Volcano, Chile: A Quantitative Geospatial Assessment in Four Communities

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ABSTRACT

Reliable methods for volcanic impact and risk assessments are essential. They provide constructive information to emergency and disaster managers, critical infrastructure providers, the insurance industry, and wider society. Post-eruption clean-up of tephra deposits is a prevalent and expensive (time and resource) activity which is often not planned for. Here, we present an overview of the clean-up efforts undertaken in four communities after the VEI 4 eruption of Calbuco volcano in 2015. We narratively reconstruct clean-up efforts in Ensenada (Chile), Junín de los Andes (Argentina), San Martín de los Andes (Argentina), and Villa La Angostura (Argentina) using semi-structured interviews, syn- and post- deposition photographs, pre- and post-event visual spectrum satellite imagery, and media reports. We compare these reconstructions with estimates based on a geospatial modelling approach adapted from Hayes et al. (Journal of Applied Volcanology 6:1; 2017). Specifically, we compare reported and geospatially derived estimates for volume of tephra removed and clean-up operation duration. We discuss: several sources of uncertainty (including observational errors and natural variance of tephra deposit thickness), reported tephra removal volume estimates, clean-up methods, land use, and temporal evolution of clean-up operation demand. The approach taken here demonstrates the utility of using simple geospatial data to develop assessments for tephra clean-up for use in response and recovery planning and quantitative volcanic impact and risk assessments.

3.1 INTRODUCTION

Widespread tephra fallout from explosive volcanic eruptions can damage the built environment (Blong 1984; Jenkins et al. 2014; Spence et al. 2005), cause infrastructure service disruption (Blong 1984; Wilson et al. 2012; Wilson et al. 2014) and generate public and environmental health issues (Horwell and Baxter 2006). These effects can lead to compounding consequences that severely disrupt social and economic activities (Sword-Daniels et al. 2014). Attempting to foresee potential impacts and provide useful information to emergency managers, critical infrastructure providers, insurance industry, and wider society is a critical component of best-practice volcanic risk reduction (Aspinall and Blong 2015; Baxter et al. 2008; Deligne et al. 2017; Loughlin et al. 2015; Magill et al. 2005; Marzocchi and Woo 2009; McDonald et al. 2017; Sparks et al. 2013; Woo 2008). One of the primary methods of developing this information is to use hazard, exposure, and vulnerability data to conduct impact and risk assessments (e.g., Biass et al. 2012; Deligne et al. 2017; Lirer and Vitelli 1998; Magill and Blong 2005). Most assessments to date have concentrated on quantifying potential life safety risks and damage to the built environment (Deligne et al. 2018; Newhall 1982). However, the disruption caused by tephra fall is often the major concern of stakeholders and removing tephra from the urban environment as part of clean-up operations is the typical response and recovery activity (Blong 1984; Durand et al. 2001; Hayes et al. 2015; Wilson et al. 2012). Relatively few, if any, assessments have quantitatively considered clean-up requirements, which limits the usefulness of these assessments for end-users, particularly if they have little or no experience managing tephra hazard (Hayes et al. 2015).

Existing assessments quantifying clean-up requirements after volcanic eruptions have focussed on assessing the potential volume (or mass) of tephra requiring removal, and the associated costs of clean-up operations, using geospatial modelling approaches (e.g., Biass et al. 2017 Johnston et al. 2001; Hayes et al. 2017; Magill et al. 2005; Zuccaro et al. 2013). Hayes et al. (2017), also attempted to model durations of clean-up operations under different eruption scenarios. Each of the above assessments contain useful information to communicate tephra clean-up requirements to stakeholders. However, there has been limited effort to evaluate how accurate these approaches are compared to actual events. This may be partially due to the limited opportunities to obtain the necessary data (Wilson et al. 2012; Wilson et al. 2014).

Model validation has been undertaken in diverse hazard and risk assessment fields to verify that models are accurate and consistent with their intended purpose (e.g., vulnerability indices: Bakkensen et al. 2016; predictive hazard and risk models: Beguería 2006; predictive landslide hazard models: Chung and Fabrri 2003; tsunami vulnerability models: Dominey-Howes and Papathoma 2007; influenza contamination: Fisher et al. 2014; power outage duration models: Nateghi et al. 2011; hurricane loss models: Watson Jr and Johnson 2004). Craig et al. (2016) evaluated several published tephra damage and disruption states, including tephra clean-up operation threshold indicators from Hayes et al. (2015), with data obtained from the 2011 Cordón Caulle eruption. The threshold indicators predicted relatively well clean-up operation scales semi-quantitatively (Craig et al. 2016). Here we build upon the work of Hayes et al. (2015) and Craig et al. (2016) to evaluate how quantitative geospatial approaches to modelling tephra clean-up requirements compare with actual clean-up operations.

In this paper we quantitatively assess tephra clean-up operation models using data from semi-structured interviews, official governmental reports, and pre- and post-deposition photographs and visual spectrum satellite imagery from four communities in Chile and Argentina following the 2015 eruption of Calbuco Volcano. Our objectives are to:

- Assess clean-up requirements at different distances from the vent and in diverse climatic settings following the Calbuco 2015 eruption, examining four communities (Ensenada, Chile; Villa La Angostura (VLA), Argentina; San Martin de los Andes (SMA), Argentina; Junín de los Andes (JDA), Argentina) (Figure 3.1);
- Retrospectively apply the Hayes et al. (2017) conceptual clean-up model based on field data (e.g., volume of tephra removed, number and size of dump trucks used); and
- Evaluate the effectiveness of the Hayes et al. (2017) conceptual modelling approach to estimate clean-up requirements in each of the four selected communities.

3.2 DATA COLLECTION

To collect the required information, we conducted semi-structured interviews with officials from organisations involved with the response to the eruption and residents affected by the eruption in both Chile and Argentina. Interviews were conducted as part of a larger research project assessing the impacts from the Calbuco 2015 eruption on infrastructure, facilities, primary industries, and public health (see Hayes et al. 2019a: Appendix A). The project was reviewed and approved by the University of Canterbury Human Ethics Committee (Ref: HEC 2016/69/LR-PS: See Appendix B). In Chile, the research was supported by SERNAGEOMIN (Chilean national geological and mining survey) and ONEMI (Chilean government agency dedicated to disaster management), and local Argentinian collaborators (CONICET/UNCO) were part of the research team for Argentinian fieldwork and data analysis. Both Chilean organisations and Argentinian research collaborators facilitated introductions and suggested appropriate agencies and individuals to contact, which they arranged and coordinated. Snowball interview sampling was also used to recruit interview participants beyond the initial agencies interviewed (Goodman 1961). Most interviews were conducted in November-December 2016, 19 months after the eruption: this allowed enough time for those involved to reflect on their experience (Craig et al. 2016; Magill et al. 2013; Wantim et al. 2018; Wilson et al. 2011). Interviews were conducted in Spanish in a variety of formats from a single interviewee and two interviewers (including translator), to larger group interviews with many interviewees and interviewers (reflecting a range of expertise and context). In most interviews, one interviewer led the questioning and at least one other interviewer recorded responses (written and/or typed). The translator was either an expert in volcanic impact assessment or had close professional support on the topic areas, including preparation and reflective discussions with volcanic impacts experts. This ensured accuracy of the translation. We asked for consent to use company names when interviewing facility staff while anonymity is given to individuals. All recorded notes (notebook and electronic devices) were kept in secure environments (locked container or drawer) at all times during field work. Following field, notebooks have been stored in secure, locked environments at the University of Canterbury. Electronic data is password protected on a secure University of Canterbury server and a secure cloud-based server. The data will be stored for at least 10 years and will subsequently be destroyed. Data sharing by the research team will be kept within the Department of Geological Sciences (now School of Earth and the Environment) at the University of Canterbury in New Zealand. Specific information we sought from interviewees included: the volume of tephra removed during clean-up operations, the quantity of different resources utilised for clean-up (e.g., dump trucks, heavy earth-moving machinery, labourers), location of disposal sites, duration of clean-up operations, and challenges associated with cleaning up. Interview notes were compiled and analysed to identify common themes. We supplement semi-structured interview data with official reports, photos, satellite imagery, and, where appropriate, local media reports. We make it clear throughout the text when these supplementary data sources are used.

3.3 THE 2015 CALBUCO ERUPTION

Calbuco volcano is in the southern Andes of Chile (Figure 3.1). The volcano is located about 30 km NE of Puerto Montt and 30 km E of Puerto Varas. There have been at least 12 historical eruptions at Calbuco over the last 226 years of Volcanic Explosivity Index (VEI) (Newhall and Self 1982) 2-4 (Global Volcanism Program (GVM) 2013). On April 22, 2015 Calbuco volcano erupted with little to no detected warning of an imminent eruption from monitoring equipment (Valderrama et al. 2016). The sub-Plinian VEI 4 eruption comprised three main eruptive pulses, and dispersed tephra in a predominantly NE direction (Figure 3.1; Van Eaton et al. 2016). The bulk erupted volume of the eruption has been estimated as 0.56 ± 0.28 km^3 (Van Eaton et al. 2016). Tephra characteristics in each of the four case study communities are shown in Table 3.1.

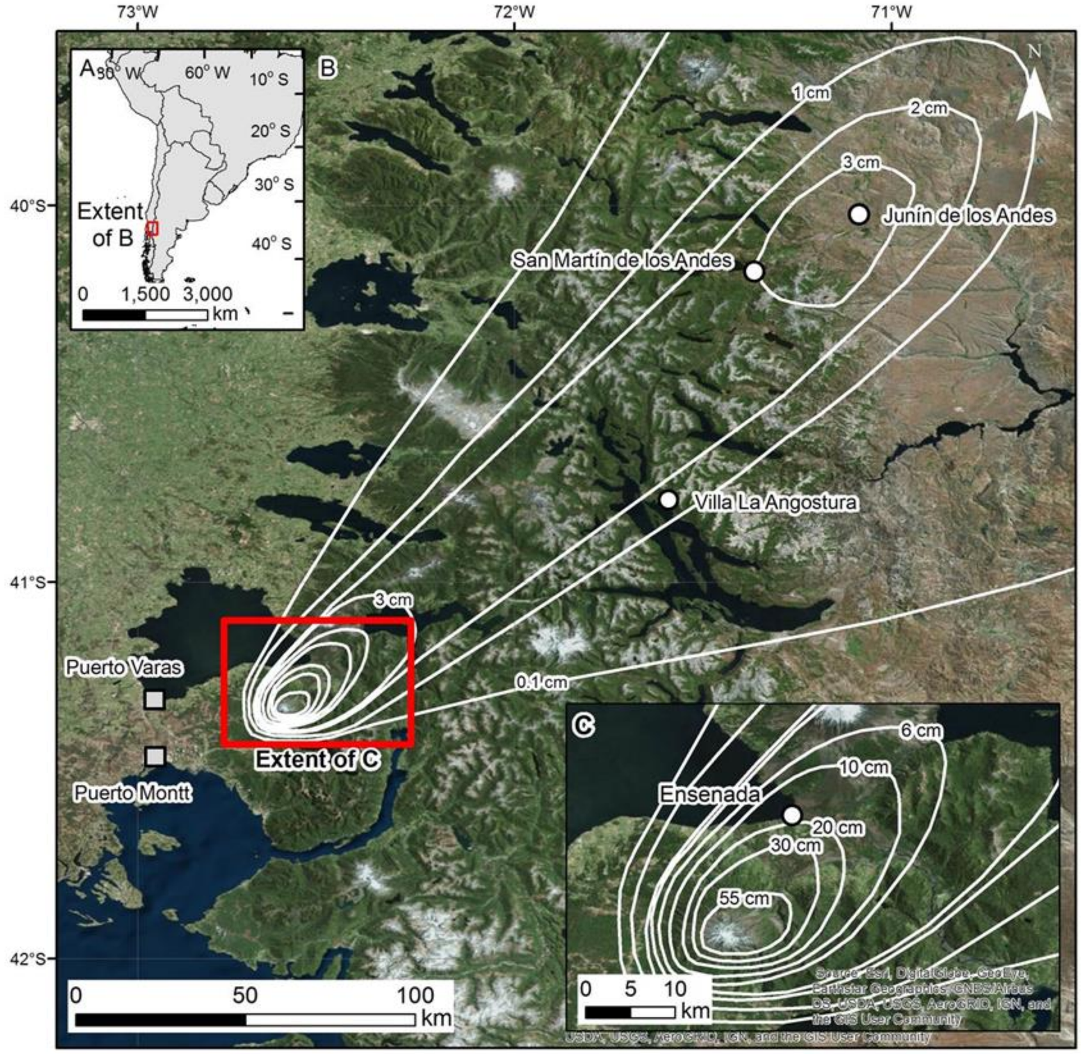

Figure 3.1: A) Location of study area, B) Tephra distribution from the Calbuco 2015 eruption with thickness in cm (Van Eaton et al. 2016) and cities mentioned in the text (squares) and our selected studied areas (circles), C) Proximal tephra distribution near Ensenada, Chile. Aerial imagery sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

3.4 CLEAN-UP IN STUDY COMMUNITIES

In this section we discuss the clean-up response for each community, in order of increasing distance from the volcano. Where possible we quantify the clean-up resources required, the duration of the clean-up operation, and volumes of tephra removed.

Table 3.1: Climatic and tephra characteristics of each case study (Peel et al. 2007; Reckziegel et al. 2016; Villarosa et al. 2016; Romero et al. 2016; van Eaton et al. 2016).

Characteristic	Ensenada, Chile	Villa La Angostura, Argentina	San Martín de los Andes, Argentina	Junín de los Andes, Argentina
Köppen-Geiger climate classification	CfB: Warm summers and no dry season	CfB: Warm summers and no dry season	CsB: dry and warm summers	CsB: dry and warm summers
Distance from Calbuco (km)	13	100	170	200
Measured tephra thickness (cm)	11-17 near village centre, 1-35 in surrounding inhabited areas	0.2 – 0.3	0.5 - 3	0.9 – 3+
Isopach thickness (cm, interpolated from Figure 3.1)	10-20 near village centre, 0.1-55 in surrounding inhabited areas	1 - 2	2 - 3	3+
Grain size φ	Polymodal, identified modes: -2 (4 mm), -1 (2 mm), 0 (1 mm)	Bimodal, identified modes: 3 (0.1 mm), 5 (0.02 mm)	Bimodal, identified modes: 4 (0.06 mm), 5 (0.02)	Bimodal, identified modes: 4 (0.06 mm), 5 (0.02 mm)

3.4.1 Ensenada, Chile

Ensenada is a sparsely populated rural settlement situated 10-15 km NE of Calbuco volcano. It is serviced by one major road, Route 225 (Figure 3.2). Most residents live in smaller settlements within Ensenada along Route 225; narrow local gravel roads lead to farms. The permanent population of Ensenada is approximately 4,000, but during the tourism season (December - February) it can increase to over 10,000. Ensenada was evacuated when Calbuco erupted in April 2015 (Hayes et al. 2019a: Appendix A). Route 225 was affected by up to 20 cm of tephra from the eruption, which was only accessible by 4WD vehicles (Hayes et al. 2019a: Appendix A). Consequently, a priority of the emergency response was to restore road connectivity between Puerto Varas and Ensenada for evacuation purposes (Hayes et al. 2019a: Appendix A). Prior to this eruption, there were no plans for tephra clean-up operations, but the Oficina Nacional de Emergencia del Ministerio del Interior (National Emergency Office of the Ministry of the Interior, ONEMI) had support agreements with contractors to help mobilise heavy machinery during emergencies (Hayes et al. 2019a: Appendix A). Road clean-up was coordinated by the Los Lagos Dirección de Vialidad (roads department) within the Ministerio de Obras Públicas (Ministry of Public Works) (MOP), and the Municipality of Puerto Varas contributed to these operations by mobilising road graders. To clear and reopen the road between Ensenada to the west and Puerto Octay to the north, graders were used to push the bulk of the tephra to the sides of the road (Figure 3.3a). Grading of the roads to a driveable standard was complete within 1-2 days. Approximately 50 heavy machines (including bobcats, diggers and loaders) were then used to load tephra into 60 six-wheeler dump trucks, which transported tephra to an initial staging site before final transport to several permanent disposal sites in the region (Hayes et al. 2019a: Appendix A). Once the bulk of the tephra had been removed, road brooming using two street sweepers and washing using eight water trucks was undertaken to remove the fine tephra residue remaining. It took approximately one month to clear most of the tephra from roads around the volcano, although some small local gravel roads still had tephra on them in December 2016 (Hayes et al. 2019a: Appendix A).

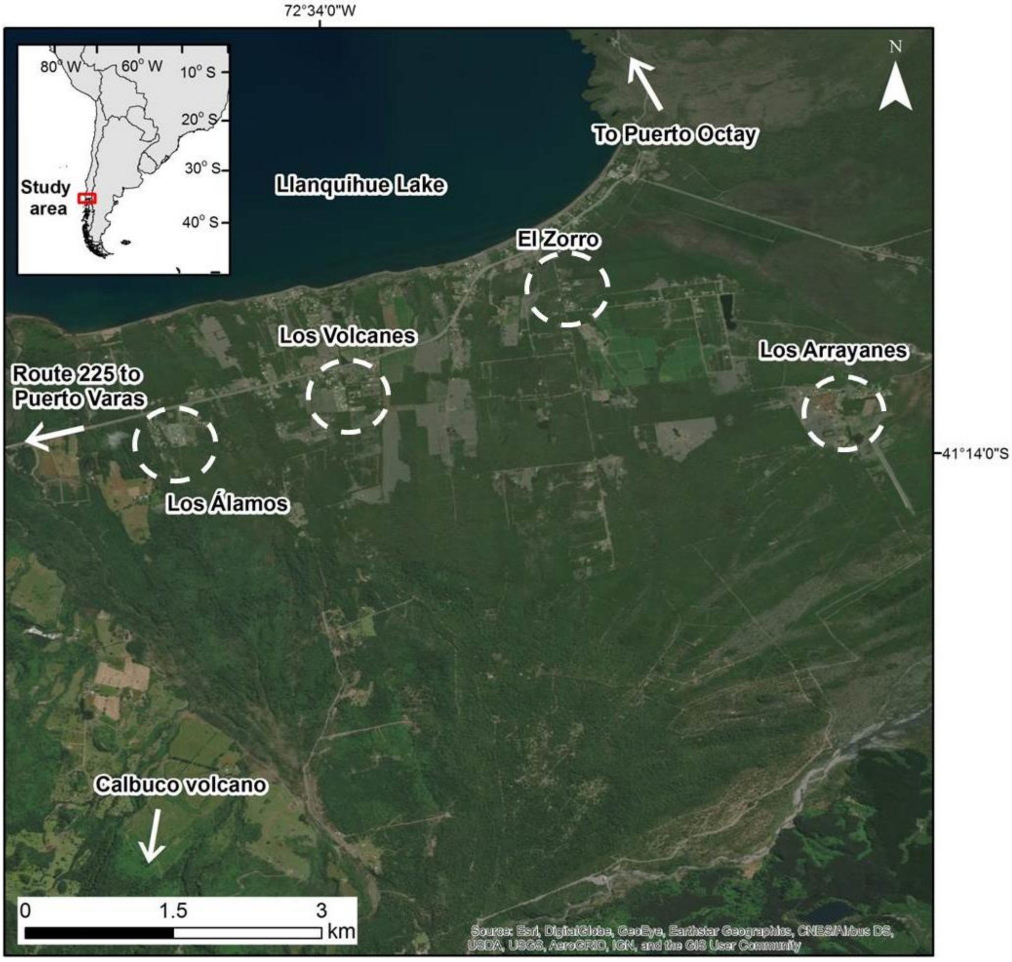

Figure 3.2: Residential communities that make up Ensenada, Chile. Aerial imagery sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Most private residential properties in Ensenada are located along Route 225 or in the communities of Los Álamos, Los Volcanes, El Zorro, and Los Arrayanes (Figure 3.2). These communities were within the evacuation zone established by ONEMI in response to the 2015 eruption. Evacuated property owners were concerned about heavy rain forecasted for the days following the eruption, as they feared that it would increase the weight of tephra on roofs and exacerbate building damage (Hayes et al. 2019b: Chapter 4). These concerns led authorities to allow a controlled daytime return of residents into Ensenada to clean their properties, but only between 8 a.m. – 5 p.m. Over 1,000 military personnel and volunteers helped clean up properties. Cleaning of residential properties began by sweeping tephra from building roofs into piles on the ground. Tephra was then shovelled into wheelbarrows and dumped at the roadside for bulk collection using heavy machinery. One person was hospitalised during clean-up activities after falling through a skylight obscured by tephra whilst cleaning a roof (Hayes et al. 2019a: Appendix A). On 31 April 2015, a third eruptive pulse occurred whilst clean-up was being conducted, forcing an immediate evacuation of the area. Clean-up of most private properties was complete within six months. However, due to a high rate of absentee owners of holiday homes, in December 2016 the Dirección de Vialidad was still fielding calls to pick up tephra that had been dumped on the road side, and substantial amounts of tephra were observed on fields in the area.

Over 300,000 m^3 of tephra was collected and disposed of, mostly on private land of volunteers willing to accept the tephra to fill in topographic depressions (Figure 3.3e & 3f). No stabilisation efforts were undertaken to reduce potential remobilisation at disposal sites as the grainsize of the tephra fall deposit was considered sufficiently large (see Table 3.1) for stabilisation to be unnecessary (Hayes et al. 2019a: Appendix A). In this case, the tephra naturally revegetated. We note this is atypical: many areas affected by previous large tephra falls in Chile such as Hudson in 1991 and Chaitén in 2008 suffered on-going remobilisation issues, particularly for fine grained deposits in arid environments (Hayes et al. 2015; Hayes et al. 2019a: Appendix A; Wilson et al. 2011). Los Lagos has a temperate climate with an average annual rainfall rate of 1942 mm (Climate-Data.org 2019), but we do not know if this aided clean-up activities by suppressing remobilisation.

The total cost for the road clean-up coordinated by MOP was calculated at US$1.3 million (2015 value; we report in 2015 US$ throughout this paper).

Approximately 80% of this was for machinery hire, maintenance, contractors, and fuel. The remainder was for health, safety, and hygiene, information and communication, and office materials. An existing agreement with contractors to provide assistance during emergencies ensured the cost of road clean-up was set at a fixed rate. These contracts are negotiated every four years and MOP credited them for keeping costs relatively static across each four-year period.

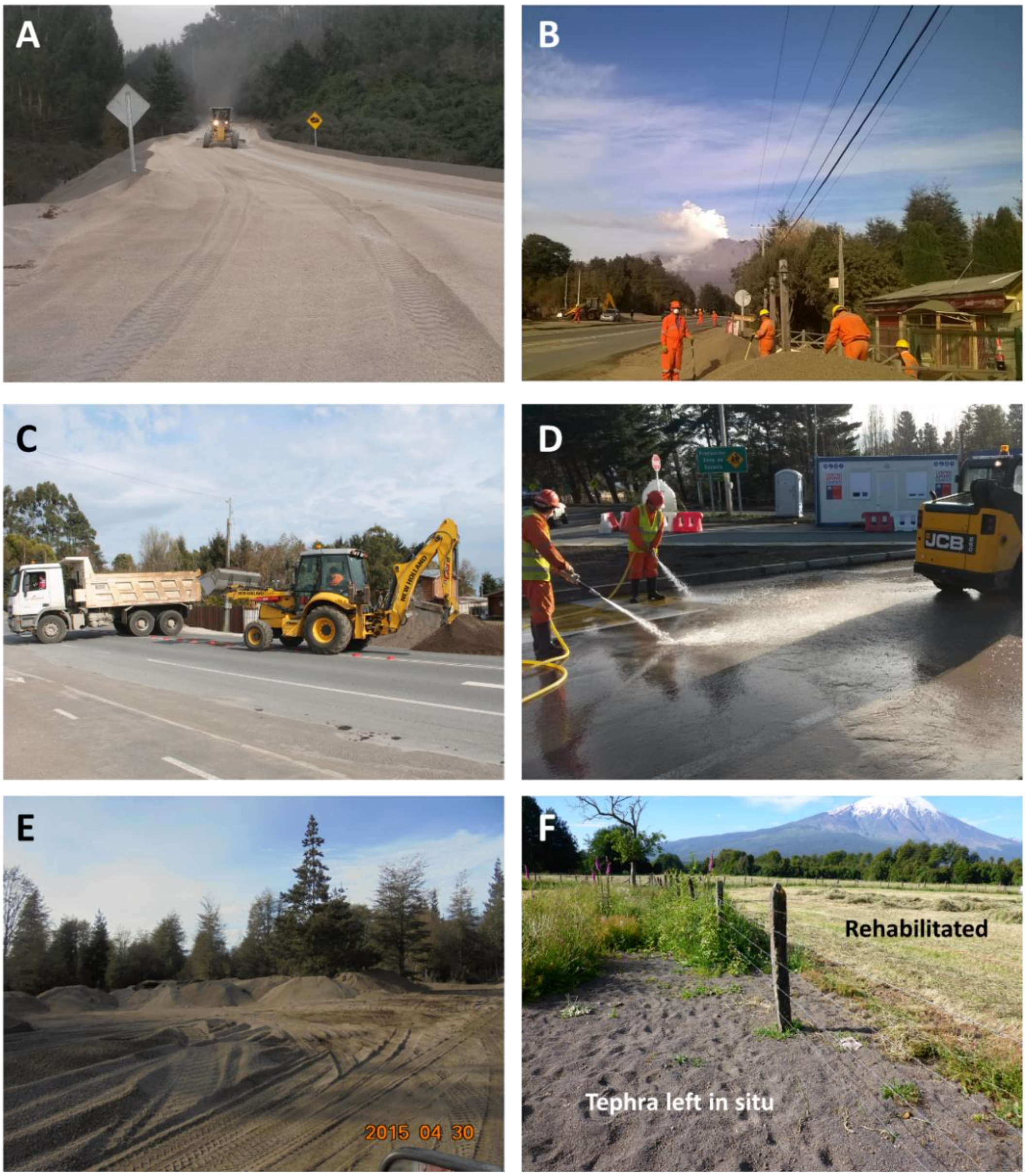

Figure 3.3: Clean-up in Ensenada, Chile. A) Grader moving tephra from centre of road (photo: MOP, Date: 24 April, 2015), B) workers removing tephra from properties and placing in piles at roadside (photo: MOP, Date: 30 April, 2015) C) bulk removal of tephra using heavy machinery and dump trucks (photo: MOP, Date: 22 September, 2015), D) washing roads of fine tephra residue (photo: MOP, Date: 11 June, 2015), E) a tephra disposal site (photo: MOP, Date: 30 April, 2015), F) rehabilitated farm land affected by ~20cm of tephra (Date: 2 December, 2016).

Clean-up of private properties and farms was expensive for the property owners. A study by the Chilean military estimated that the cost of removal of tephra from agricultural land would be on the order of 1.8 million Chilean pesos (US$2,880) per hectare, an estimate considered to be prohibitively high for many of the local farmers (Hayes et al. 2019a: Appendix A). As a result, substantial volumes of tephra deposited on agricultural land were not removed and as of December 2016, many farms had not recommenced agricultural activities in the area (Hayes et al. 2019a: Appendix A). We do not have any data estimating the loss of earnings due to the eruption. The Chilean Ministerio de Agricultura (MINAGRI) expected that agricultural activities would be precluded on farms affected by over 15 cm of tephra in the immediate future due to these substantial removal costs (Hayes et al. 2019a: Appendix A). However, to rehabilitate the land some (unknown quantity) farmers removed the top 30-50% of tephra, and then ploughed and mixed the remaining tephra into the underlying soil with promising results (Hayes et al. 2019a: Appendix A; Figure 3.3F).

3.4.2 Villa La Angostura

Villa La Angostura (VLA) is a tourist town with a permanent population of ~12,000 (Ministerio del Interior, 2018a), located 100 km from Calbuco volcano in the Neuquén province of Argentina. It is situated within a temperate climate zone at the northern end of Lago Nahuel Huapi. Its economy is based on tourism, and the town has strong seasonal increases in population due to influxes of tourists (Craig et al. 2016).

Tephra deposition on the town from the 2015 Calbuco eruption was measured to be 0.2 cm (Reckziegel et al. 2016). Van Eaton et al. (2016) supporting information includes measurements on the outskirts of VLA taken on 29 April 2015 of 2 cm thick, although co-authors of the current work were unable to find thicknesses exceeding 1 cm near VLA in the days immediately following the eruption. Despite being closer to the vent than San Martín de los Andes (SMA) or Junín de los Andes (JDA), VLA received less tephra fall as it lay off the principle axis of dispersion (Figure 3.1). The clean-up for Calbuco 2015 tephra fall was reportedly much easier than the clean-up following the deposition of 20 cm of tephra from the Cordón Caulle eruption in June 2011 (Elissondo et al. 2016; Craig et al. 2016; Wilson et al. 2013), mostly due to the much smaller accumulation of tephra. The recent experience of the 2011 Cordón Caulle tephra fall had taught the community what to do during and following a tephra fall. Tephra was collected and piled from private, commercial and public properties using manual labour (e.g., brooms, shovels, wheelbarrows), and then loaded onto dump trucks using heavy earth-moving machinery before being transported to dump sites, which were already established from the 2011 event. There were only six road crews (trucks and heavy machinery) assigned to clean-up VLA, and all operations were conducted with existing staff (Gobierno de la Provincia del Neuquen 2015d). Even with relatively limited resources, clean-up was mostly complete within one and a half weeks (Gobierno de la Provincia del Neuquen 2015d) but washing of roads using pressurised water continued for a total of 20 days after initial tephra deposition to reduce remobilisation issues. Rainfall one week after the tephra fall event reportedly assisted the clean-up process by washing a small amount of fine tephra residue into the storm water system.

VLA has four disposal sites that were established for Cordón Caulle 2011 tephra and utilised for the Calbuco eruption. Sites include a mallín (low-lying floodplain or wetland) on the Route 40 from VLA to SMA (disposal site A: surface area ~6,500 m^2), a mallín along Siete Lagos Rd (disposal site B: surface area ~ 5,400 m^2), a back road beside the Rio Piedritas (disposal site C: surface area ~4,500 m^2), and an old quarry near Puerto Manzano (disposal site D: surface area ~20,000 m^2) (Figure 3.4). Tephra that was dumped at disposal site B was about 2 m thick (compacted) and allowed to revegetate naturally. However, most of the tephra disposed in each location was from the 2011 Cordón Caulle eruption; there is no data available on the amount of tephra from VLA that was disposed after the Calbuco eruption at each disposal location, possibly due to the very low volumes collected.

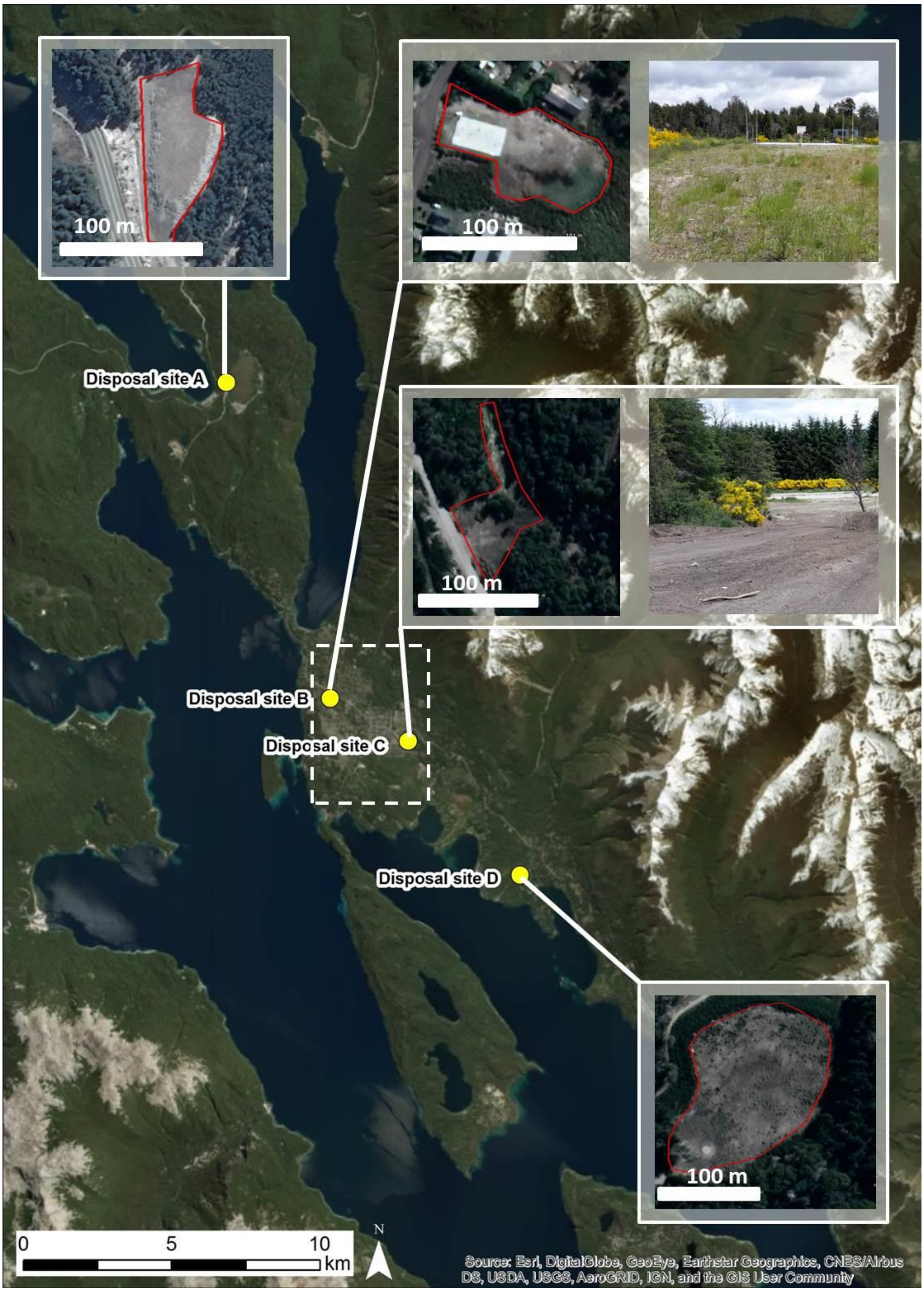

Figure 3.4: Disposal sites used for tephra deposition in VLA. Aerial imagery sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community dated 26 March 2018. Ground photos from December 2016 (20 months post deposition). White dashed box is approximate extent of VLA.

3.4.3 San Martín de los Andes, Argentina

San Martín de los Andes (SMA) is a city of ~30,000 inhabitants located within the Neuquén province of Argentina approximately 170 km NE of Calbuco volcano (Ministerio del Interior 2018b). SMA lies along the principle axis of dispersion and was affected by tephra fall accumulating up to 1 cm from the 2011 Cordón Caulle eruption (Alloway et al. 2015). The experience and lessons learned from this were utilised for cleaning the tephra deposited during the 2015 Calbuco eruption. A key lesson was to involve residents in the clean-up efforts early as this reduced the load on municipality resources. Measured tephra thickness from the 2015 Calbuco eruption of 0.5 cm in the centre of the SMA urban area was reported by Reckziegel et al. (2016). However, Van Eaton et al. (2016) supporting information includes estimated thicknesses of 2-3 cm made on 29 April 2015 at Route 40 approximately 500 m south of SMA. Police, fire, army personnel, and approximately 1,000 volunteers helped with the clean-up of city streets and facilities (e.g., schools and airport). Schools were cleaned within three days, but it took 50 volunteers ten days to complete the clean-up at Aviador Carlos Campos Airport. Fourteen road crews, using dump trucks and snow ploughs, were used to clean up SMA streets (San Martin Diario 2015). Hospital, police/fire station areas, and health centres were prioritised for clean-up, and then bus service routes were cleaned to reduce remobilisation effects. Roads were cleaned using graders, diggers, and trucks, but later re-contaminated when people dumped tephra from their properties at street corners for collection. This required a second cleaning of roads at the end of the clean-up operation. The downtown area took approximately 2 weeks to complete clean-up, and clean-up of the entire town took about two months.

During interviews we conducted in Argentina, officials in SMA expressed that they considered the Calbuco 2015 tephra more problematic to clean up, the reason for which they attributed to Calbuco tephra being more easily remobilised than the 2011 Cordón Caulle tephra. The Calbuco 2015 clean-up was also the first considerable clean-up required in SMA, as the Cordón Caulle tephra was very thin and discontinuous. SMA officials said that clean-up methods worked well for the Cordón Caulle tephra, which washed into the drainage system and into Lake Lacar. However, the Calbuco tephra become cementitious and clogged drains. This meant that suction machines were required to clear the drains, and shovels had to be used where substantial mixing of leaves and tephra occurred. As a consequence, the public were advised to stop using water for clean-up.

Clean-up began on 24 April 2015 and was conducted between the hours of 7 a.m. and 2 p.m. each day. These hours were adopted to avoid overtime being charged to the municipality. By 5 May 2015 approximately 3,000 m^3 had been removed from SMA, an average of 200 m^3 per day (Gobierno de la Provincia del Neuquen 2015a). Another estimate reported in the media on 11 May 2015 was 6,000 m^3 (300 m^3 per day) (RioNegro 2015). The final estimate reported by Gobierno de la Provincia del Nequen was 10,000 m^3 on 14 May 2015 (500 m^3 per day) (Gobierno de la Provincia del Neuquen 2015c). In total it was reported to us during interviews that 2,500 truckloads (capacity of ~5 m^3) were required to remove the tephra from SMA. Assuming these trucks were at capacity, this yields a total clean-up volume of 12,500 m^3 removed over the two-month long clean-up operation; an average tephra removal rate of 200 m^3 per day. An unknown, but likely small, amount of tephra was left behind on gravel roads.

There were no pre-existing plans for disposal of tephra. Officials dumped the tephra near the lake (Figure 3.5), but other locations (e.g., on military property) were utilised for smaller (but unmeasured) volumes of tephra.

Figure 3.5: Dump site near Lácar Lake for tephra from San Martín de los Andes (Photo: Daniel Blake, taken December 2016).

3.4.4 Junín de los Andes, Argentina

Junín de los Andes (JDA) is a small town of 15,000 inhabitants located about 200 km NE of Calbuco volcano in the Neuquén province of Argentina (Ministerio del Interior 2018c). Its climate is distinctly more arid than that of SMA, despite being located only 30 km away (Figure 3.1). Compared to SMA, JDA received more tephra fall (1.5 cm in Romero et al. (2016) to an estimated 3+ cm in Van Eaton et al. (2016) supporting material) due to a secondary thickening effect (Figure 3.1). Tephra fall in JDA was very fine-grained (Reckziegel et al. 2016). As a consequence of the fine grainsize and the dry climate, tephra was easily remobilised by aeolian and anthropogenic processes (Figure 3.6). To counteract this, attempts were made to keep the tephra permanently damp using watering trucks.

Figure 3.6: Remobilisation of tephra in Junín de Los Andes in April 2015 (photos courtesy of Bomberos de Junín de Los Andes).

Clean-up of tephra from JDA began on 24 April 2015 (Gobieno de la Provincia del Neuquen 2015a). To conduct clean-up, JDA was divided into five sectors, each with two sprinkler trucks, a motor grader, one or two loaders, and two dump trucks (Gobieno de la Provincia del Neuquen 2015a). However, 50 dump trucks were in operation when the clean-up was at its peak. The local volunteer fire brigade mobilised to help with the clean-up of properties and to remove tephra from roofs (Figure 3.7). Dry brushing was mostly used to remove tephra from roofs. In some instances, water was used to remove tephra from roofs, but this led to the tephra becoming cemented and sticking to the surface.

Figure 3.7: Cleaning tephra from roofs in Junín de Los Andes (photos courtesy of Junín de Los Andes Bomberos, Date: April 2015).

By 29 April 2015, 5,000 m^3 of tephra had been removed from JDA and taken to the tephra dump, an average tephra removal rate of approximately 800 m^3 per day (Gobierno de la Provincía del Neuquen 2015b). On 4 May 2015, the Undersecretary of Planning and Public Services reported that about 15,000 m^3 of tephra had been removed (tephra removal rate of 1,400 m^3 per day) and forecast that about one more month of work was required to complete clean-up (Gobierno de la Provincia del Neuquen 2015a). As of 11 May 2015, the estimate was reported at 32,000 m^3 (1,800 m^3 per day) (RioNegro 2015), and it was estimated that approximately 40,000 m^3 of tephra were removed in total from JDA as of 14 May 2015 (1,900 m^3 per day) (Gobierno de la Provincia del Neuquen 2015c).

A local garbage dump was used to dispose of the collected tephra (Figure 3.8; Gobierno de la Provincia del Neuquen 2015a). Planned remediation for the site was to add a soil cap and vegetate to prevent remobilisation of the tephra, but this had not been completed as of April 2018.

Figure 3.8: Former garbage dump where Junín de los Andes tephra was dumped (Photo: Carol Stewart, December 2016).

3.5 METHODOLOGY

In the following subsections we outline our approach, adapted from Hayes et al. (2017), to model tephra removal volumes and clean-up durations.

3.5.1 Removed tephra volume

It is useful to forecast the amount of tephra to be removed when preparing for tephra clean-up operations, as it provides emergency managers with information on relative effort required (e.g., resource requirements) and constraints on the potential disposal locations (Brown et al. 2011; Hayes et al. 2015). For example, to model the volume of tephra that may need to be removed from Auckland, New Zealand after a volcanic eruption, Hayes et al. (2017) assessed how much tephra would be deposited on different urban surfaces within the urban area and then used empirically informed, but largely theoretical, tephra thickness thresholds to define what urban surfaces would have tephra removed and taken to disposal sites. To apply the model in this study, we:

- define the spatial extent of our case study communities that requires clean-up;

- obtain data relating to the proportion of different urban surfaces within that spatial extent; and
- use measured thickness data to calculate the volume of tephra requiring removal.

For VLA, JDA, and SMA, we use the extent of the built-up area to determine the spatial extent for sampling and digitising of urban surfaces (Figure 3.9). Ensenada presents an additional challenge, as the extent of the built-up area is not obvious. Instead we use the areal extent of the 4 communities that make up Ensenada and the transport corridor that connects each of them.

High quality geospatial data of urban surfaces (e.g., impervious surfaces, building footprints) were unavailable for our analysis - a common issue for many communities exposed to tephra fall across the world. Open Street Map (OSM) contains reasonable quality road lines, but in our study area the quality for building footprints is highly variable and does not contain useful information regarding other paved surfaces, such as sidewalks, driveways and carparks. Digital Globe imagery can be used to digitally map different urban surfaces, but without an automated approach this is time-consuming and labour-intensive. Thus, we digitised buildings and paved areas (excluding roads) in a representative sample area at each location and used this to estimate the proportional area in our study locations made up of road, building, and other impervious surfaces. To do this we constructed a 100x100 m gridded area of the clean-up extent for each of our case study communities and randomly digitised impervious surfaces (except road) in the necessary number of grid cells to obtain 95% confidence level and standard error of 5%. The dates of the imagery used were:

- Ensenada = 29 November 2015
- JDA = 23 January 2013
- SMA = 10 October 2014
- VLA = 07 January 2015

Since OSM road lines are of a sufficient quality for our analysis, we converted OSM road lines into road area by creating a 3 m buffer (approximate width of a road lane in the area). We then determine the total area of the clean-up zone made up of the different urban surfaces using equation (3-1):

$$T = \frac{U}{S \times A} \tag{3-1}$$

where T = total impervious surface within the clean-up zone, U = the sum area of impervious surfaces within the sampled grid cells, S = the total area of sampled grid cells, and A = the total clean-up zone area.

We determine the quantity of tephra on each urban surface by multiplying urban surface area (m^2) by deposit thickness (m). Deposit thickness is based on published measurements and isopach maps, which we outline in detail in later sections.

Hayes et al. (2015) found that the proportional amount of tephra to be removed from urban areas scales with tephra accumulation. Thus, this scaling relationship needs to be considered when attempting to model the volume of tephra that must be removed from urban areas. Hayes et al. (2017) suggested that tephra thickness thresholds could be used to ensure tephra removal scaling is incorporated into the modelling process. The Hayes et al. (2017) thresholds were developed for use within urban areas, and more specifically for metropolitan Auckland, New Zealand, are used here (Table 3.2). Since Ensenada has a higher incidence of agricultural land use, we have also developed a refined model that incorporates the anecdotal information that only ~30% of tephra on agricultural land was removed from farms exposed to over 100 mm of tephra.

Table 3.2: Tephra clean-up thresholds used to assess tephra removal volumes for case study communities (adapted from Hayes et al. 2017).

Hayes et al. (2017) thresholds		**Ensenada thresholds refined for this study**	
Thickness (mm)	Surfaces for tephra removal	Thickness (mm)	Surfaces for tephra removal
1 – 10	Roads and airports	1 – 10	Roads
10 – 200	As above, with impervious surfaces from private properties included	10 – 100	As above, with impervious surfaces from private properties included
>200	Tephra removed from all surfaces	≥100	All impervious surfaces and 30% of tephra from all other surfaces removed

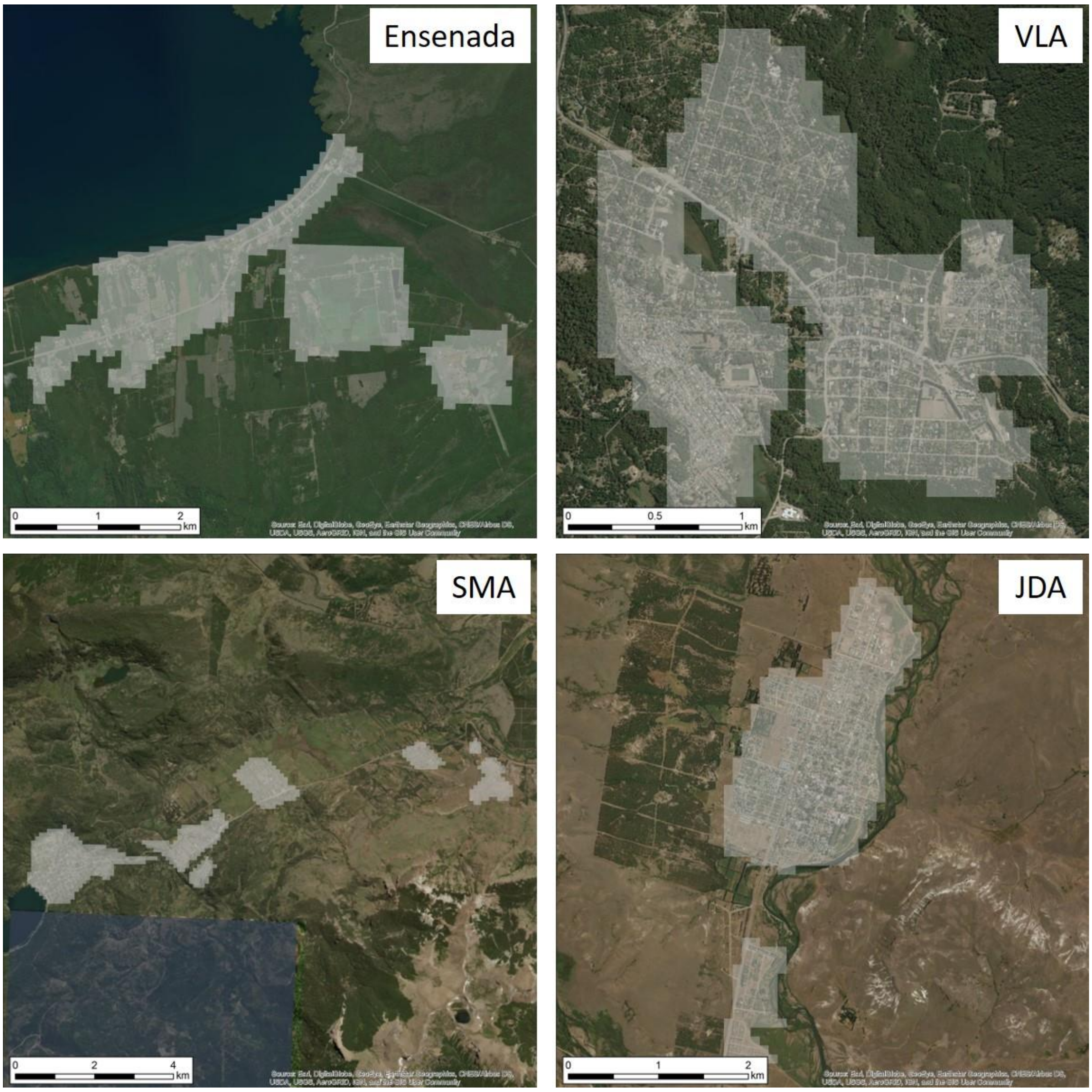

Figure 3.9: Spatial extent (grey shaded area) of clean-up zones used for geospatial clean-up modelling. North at top. Aerial imagery sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Uncertainty of tephra thickness and tephra removal volumes

To evaluate how effective the modelling approach is at forecasting clean-up volume it is necessary that model outputs and reported volumes consider the same sources of uncertainty. For example, tephra can compact in a very short time and this will considerably influence the estimated volumes of tephra removed. In the subsections below we outline areas of uncertainty within our analysis and how we have quantified each so that reported and modelled estimates are considering the same sources of uncertainty.

Natural variability

An assumption in the construction of tephra isopach maps is that thickness is uniform over local areas (Engwell et al. 2013). However, natural variability of the deposit can result in localised thickening or thinning (Engwell et al. 2013). Remobilisation of tephra deposits through aeolian, hydrological, or anthropogenic processes are also important sources of natural variability of tephra thickness locally (Blong et al. 2017; Collins and Dunne 1986; Collins et al. 1983; Wilson et al. 2011). Localised thickening can also occur in topographic low points (Engwell et al. 2013). Natural compaction of tephra can reduce tephra thickness by as much as 50% and much of it can occur in the first few weeks of deposition (Blong et al. 2017; Engwell et al. 2013; Hildreth and Drake 1992; Thorarinsson 1954). This means it is necessary to obtain tephra thickness measurements that are representative of the deposit variability. Therefore, the number of measurements made, time elapsed between deposition and measurement (potential for multiple fall events, remobilisation, and compaction), and locations of measurements are important sources of uncertainty. In this work we use the actual measurements made in or near each case study community. The exception to this is Ensenada, which exhibited a wide range in tephra thickness across the community (0.1 cm to over 55 cm) because it spanned the outer edge of the tephra deposit axis. Therefore, we use the isopach map published in Van Eaton et al. (2016) for Ensenada.

Observational error

Studies assessing observational errors associated with making tephra thickness measurements have found ranges of 3 – 25% (Le Pennec et al. 2012) and 2 - 65% (Engwell et al. 2013). Bonadonna et al. (2015) also concluded that tephra thickness measurements associated with explosive volcanic eruptions can have a cumulative uncertainty of up to ±30% when averaged across an entire deposit (5-20% associated with observational uncertainty). We assign a ±30% error to each thickness measurement used in this study.

Determining tephra thickness in study locations

We are reliant on published sources for data on the tephra thickness in each of our case study locations due to our volcanic impact reconnaissance trip taking place 19 months following the eruption of Calbuco. Published data on tephra thickness in each of our study locations demonstrates considerable uncertainty (Table 3.3). Thickness data sourced from Reckziegel et al. (2016) was reportedly collected shortly following the eruption and care was taken to ensure samples were pristine and unaffected by aeolian or hydrological remobilisation forces.

Table 3.3: Tephra thickness measurements taken in or near the case study communities and used to model volume in this study.

Location	Minimum tephra thickness (cm) [Source]	Maximum tephra thickness (cm) [Source]
Ensenada, Chile	0.3 [Van Eaton et al. 2016][a]	55 [Van Eaton et al. 2016][a]
VLA, Argentina	0.2 [Reckziegel et al. 2016][b]	0.3 [Van Eaton et al. 2016][c]
SMA, Argentina	0.5 [Reckziegel et al. 2016][b]	3 [Van Eaton et al. 2016][d]
JDA, Argentina	0.9 [Van Eaton et al. 2016][e]	> 3 [Van Eaton et al. 2016][f]

[a] 27 – 30 April 2015
[b] Date not published, but reportedly shortly following the eruption
[c] 3 July 2015
[d] 28 April 2015
[e] 4 July 2015
[f] 28 April 2015

Geospatial data uncertainty

Uncertainty associated with geospatial data could also influence modelling outputs as the extent of different urban surfaces is a key input into computing tephra removal volumes. Minor geospatial errors may have entered our analysis as our intention was not to digitise the urban fabric with a high level of precision, but to instead demonstrate that such data could be generated to a satisfactory standard quickly. As we were digitising from Digital Globe imagery, shadows can make urban features such as buildings appear larger than they are. Also, topological errors such as over- and undershoots, and slivers are possible (see: Maraş et al. 2010). Within the OSM data, it is possible some roads are missing or that some roads are wider or narrower than the 3 m buffer we assigned. We include an assumed error of ±5% to the digitised and OSM geospatial data to account for these potential sources of error.

Reported volume of tephra removed

To compare our model outputs with observed events it is necessary to have accurately reported volumes of tephra that were removed from case study communities. However, it is rare that the volume of tephra that is removed from urban areas is precisely reported (Hayes et al. 2015). Estimates are often based on the number of truck loads or from tephra piles at disposal sites, which are not exact values (Hayes et al. 2015). It is difficult to ascertain whether volume estimates account for compaction that may have happened prior to tephra removal through natural or anthropogenic processes (e.g., dampening of deposit to reduce remobilisation) or subsequently after removal (process of loading onto truck, or at a disposal location). Given that tephra deposits can rapidly naturally compact by as much as 50% (Blong et al. 2017) we assume an error of ±50% to the estimates of tephra removal volumes.

Clean-up operation duration

Hayes et al. (2017) developed a geospatial network analysis approach to estimating clean-up duration to calculated how long it would take a fleet of trucks to transport a given distributed volume of tephra to pre-determined tephra disposal sites. To estimate the duration of a clean-up operation, it is necessary to know how many truck loads are required to transport the tephra from pickup points to disposal sites. To evaluate tephra clean-up operation duration Hayes et al. (2017) developed equation (3-2); see Hayes et al. (2017) for details):

$$T = \frac{(F_t \times 2)+(F_c \times (L_t+U_t))}{H_d} \qquad (3\text{-}2)$$

where T = clean-up duration (days), F_t = fleet hauling time, F_c = number of truck loads to remove the tephra, L_t = loading time, U_t = unloading time, and H_d = hours per day transportation works occur. Hayes et al. (2017) utilised high quality road network datasets for Auckland, New Zealand to conduct geospatial network analysis between pickup points and disposal locations. In the present work, we do not have equivalent datasets. Instead, we utilised a conceptually similar, but modified equation (3-3):

$$T = \frac{(T_L \times N_t)\times(F_t \times 2)+ (L_t+U_t))}{H_d} \qquad (3\text{-}3)$$

where T = clean-up duration in days, T_L = number of truck loads required (volumetric capacity of truck / total removal volume), N_t = number of trucks available, F_t = fleet hauling time (hours), L_t = loading time (hours), U_t = unloading time (hours) and H_d = number of hours per day transportation works occur. The major modification is that we have assumed an average travel time to disposal sites, rather than precise origin-destination network modelling.

In Table 3.4 we outline the parameters used for tephra clean-up duration modelling. The six-wheeler trucks utilised to clean up Ensenada have a maximum volumetric capacity of ~10 m^3, whereas the smaller four-wheeler trucks utilised in the other case study locations have a maximum capacity of ~5 m^3 (Hayes et al. 2017). Not all trucks will be filled to capacity: it is probable that some will be underfilled. To account for this, we have assumed that a truck will be at least 75% of its maximum capacity before travelling to a disposal site. To determine the number of truck loads (TL) for Ensenada and JDA we use the total volume reported by interview participants as being volume removed (±50%) divided by the volumetric capacity of the trucks. For SMA, an interview participant estimated that 2,500 truckloads were taken to the disposal site, so we use this value rather than deriving T_L. We have no estimates of volume removed at VLA, so we have utilised estimates based on our geospatial modelling approach outlined above. We also use modelled volumes for the other three case study communities to compare how the results differ depending on whether using modelled volumes or reported volumes.

The number of trucks (N_T) utilised for each of our case study locations are based on interview participants' estimates as well as estimates made by officials in local media. For VLA, SMA, and JDA estimates are based on the number of 'road teams', which consisted of both diggers and trucks. We have assumed a 1:1 ratio of diggers to trucks. We note that the number of trucks utilised in a clean-up operation can fluctuate from a small initial number to a peak corresponding to when reinforcements arrive, before a decline as demand decreases. We assume that truck numbers reported to us reflect peak deployment. However, for JDA it was reported that initially only ten trucks were used until further reinforcements arrived. We do not know the exact amount of time ten trucks were used or when other assets arrived, so we have accounted for this uncertainty by including a range of 10-25 trucks used for JDA clean-up.

The time it takes for a truck to travel to or from a disposal site (Ft) is estimated based on using drive time estimates from the centre of each case study town to a disposal site. We have set the loading and unloading times as static at 5 minutes for each. Finally, each of our case study locations continued clean-up activities for approximate 8 hrs per day.

Monte Carlo modelling

As with Hayes et al. (2017), we utilise Monte Carlo sampling (10,000 iterations) as a method to incorporate uncertainty into the modelling approach. This involves assigning probability distributions around uncertain parameters within the equations described in the above subsections (e.g., duration to disposal site, total area affected, tephra thickness). We have used uniform distributions to represent each of the uncertain parameters. We provide the spreadsheets used to compute these values in Supplementary Material 1.

Table 3.4: Parameters used to model tephra clean-up operation duration.

Location	Truck capacity	T_L	N_t	F_t (hours)	L_t (Hours)	U_t (Hours)	H_d (Hours)
Ensenada	7.5 – 10	15,000 - 60,000	60	0.375 – 0.5	0.08	0.08	8
VLA	3.75 - 5	822 – 2,657	3	0.2 – 0.25	0.08	0.08	8
SMA	N/A	2,500	7	0.2 – 0.25	0.08	0.08	8
JDA	3.75 - 5	4,000 – 16,000	10 - 25	0.2	0.08	0.08	8

3.6 RESULTS

3.6.1 Surface area of clean-up zones

We present the results of our geospatial analysis of urban surfaces in each case study location in Table 3.5. Ensenada has the lowest proportion of urban surfaces requiring clean-up (0.4 – 2 %) out of our case study communities, with VLA (10%), JDA (13%), and SMA (18%) containing considerably higher proportions of impervious surfaces. No settlements in Ensenada were exposed to tephra fall of less the 100 mm (only roads), which is why no impervious surfaces (building footprint or paved areas) were sampled.

3.6.2 Volume removed

Estimates of the volume requiring removal from different surfaces are presented in Figure 3.10. For Ensenada, only the 'refined' model fits within the range of the reported removal volume, and the calculated tephra removal volume is 450,000 m^3. For SMA, all models fit within the uncertainty range, but 'total volume removed' only falls within the upper limit of the reported removal uncertainty range. However, 'road only' and 'road and impervious surface' models still assign a considerable probability of exceedance that falls outside of the uncertainty range and the expected value for the tephra removal volume is 33,000 m^3. The 'roads and impervious surface' model for JDA appears to almost perfectly match the tephra removal uncertainty range, and the expected value of 38,000 m^3 is not substantially dissimilar to the reported volume of about 40,000 m^3. We do not have any data on the reported volume removed from VLA, but our estimates appear reasonable considering the thinner tephra fall.

Table 3.5: Geospatial analysis of urban surfaces in case study locations. N/a indicates that no grid cells fell within these thickness ranges

Location	Area of exposed assets (m^2)	Area sampled (m^2)	Sampled area that is impervious surface (m^2)	Percentage of total area that is impervious surface (%)	Extrapolated area that is impervious surface (m^2)	Total area of road (m^2)
Ensenada 1 – 5 mm	20,000	0	n/a	n/a	n/a	20,000
Ensenada >5 – 10 mm	27,000	0	n/a	n/a	n/a	27,000
Ensenada >10 – 20 mm	14,000	0	n/a	n/a	n/a	14,000
Ensenada >20 – 30 mm	14,000	0	n/a	n/a	n/a	14,000
Ensenada >30 – 60 mm	60,000	0	n/a	n/a	n/a	60,000
Ensenada >60 – 100 mm	99,000	0	n/a	n/a	n/a	99,000
Ensenada >100 – 150 mm	146,000	51,000	1,000	2	3,000	70,000
Ensenada >150 – 200 mm	5,163,000	1,305,000	26,000	2	102,000	146,000
Ensenada >200 – 300 mm	878,000	236,000	1,000	0.4	3,000	28,000
Ensenada >300 mm	15,000	0	n/a	n/a	n/a	15,000
VLA	4,220,000	2,010,000	196,000	10	412,000	1,175,000
SMA	7,530,000	2,550,000	451,000	18	1,330,000	1,467,000
JDA	4,910,000	2,150,000	288,000	13	658,000	942,000

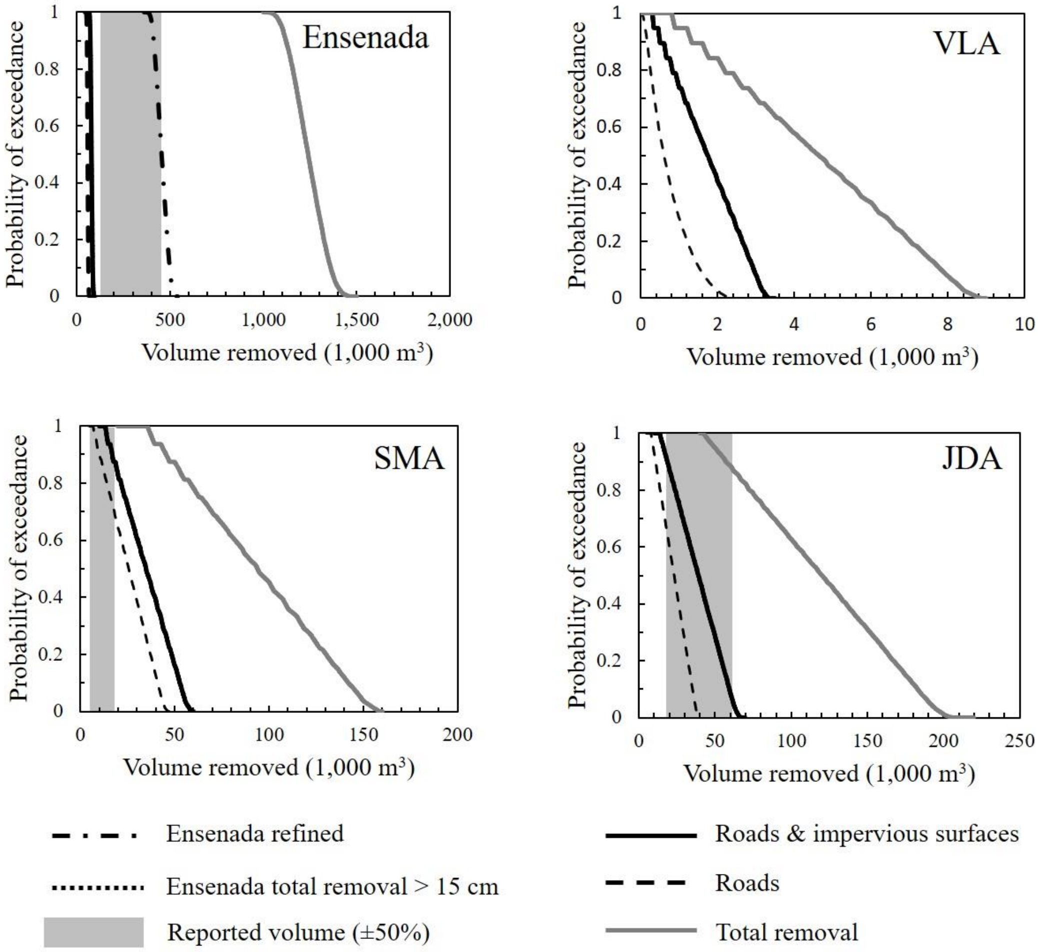

Figure 3.10: Geospatial model volumes. Grey shaded area = range of reported volume removed. Note: No reported removal data for VLA.

3.6.3 Clean-up duration

Estimates of clean-up operation duration for roads appear to broadly reflect the actual duration (Figure 3.11). However, for Ensenada the duration for total clean-up including private properties appears to be considerably underestimated. Using modelled tephra volume, VLA clean-up appears to underestimate the clean-up duration, but only by a few days. Large uncertainties of the tephra removal volume contribute to considerable ranges for clean-up operation duration for both SMA and JDA. Using the reported removal volume for SMA, the expected value for the clean-up duration is 4 weeks, which is half the reported duration. Using the modelled tephra removal produces an expected value for clean-up operation duration of 13 weeks, approximately 5 weeks longer than the reported duration. For JDA, curves using the modelled and reported volumes produce similar outputs. The reported duration of clean-up in JDA was 6 weeks, which is the same as the expected value for clean-up duration for both the modelled and reported tephra volume.

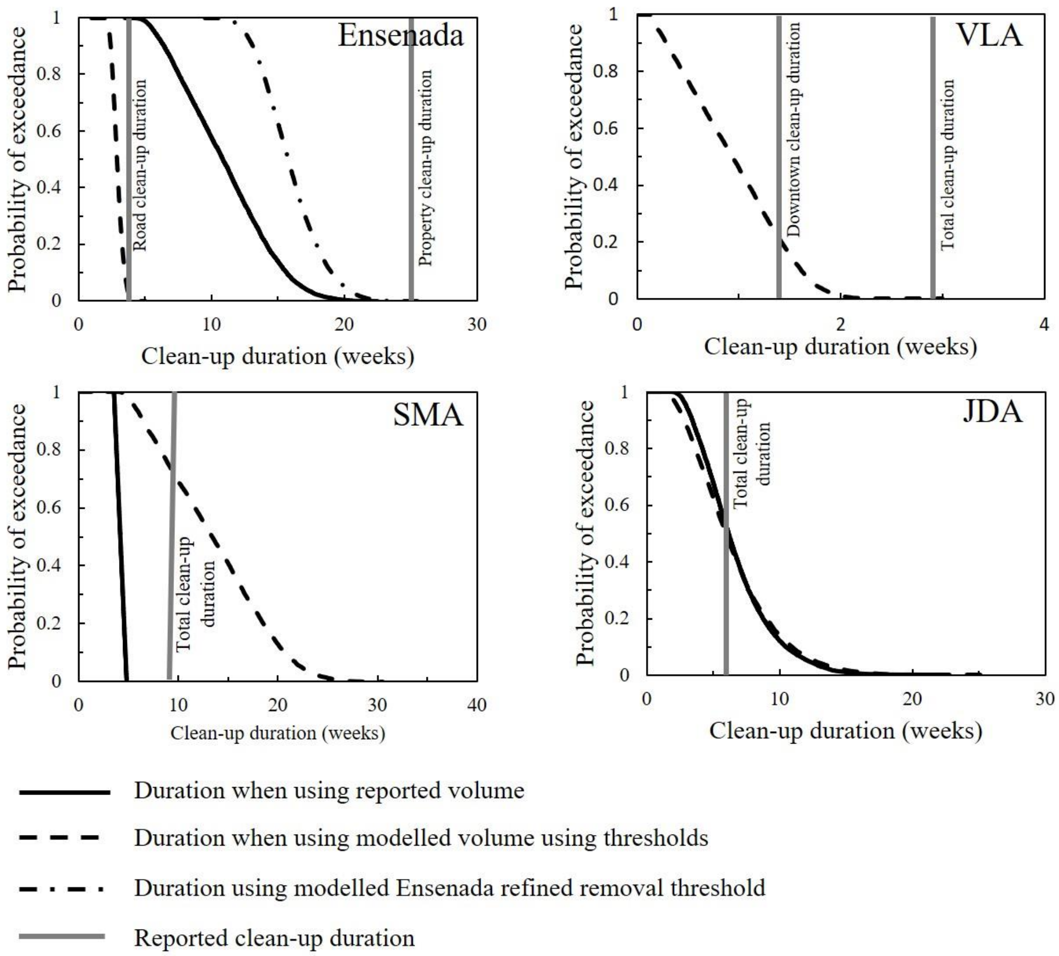

Figure 3.11: Clean-up duration modelling outputs. Note: no reported volume for VLA.

3.7 DISCUSSION

3.7.1 Performance of the geospatial clean-up model

Hayes et al. (2015) found that clean-up operations are influenced by complex interactions between physical factors (e.g., erupted volume, column height, grainsize, wind speed and direction, rainfall) and social factors (e.g., social priorities, prior planning, previous experience, and infrastructure interdependencies). Insufficient evidence is currently available to quantitatively account for each of these factors, which means logical simplifications have been required to quantitatively geospatially model tephra clean-up. In the following subsections, we discuss how the conceptual geospatial model put forward by Hayes et al. (2017) performed when evaluated against real observations from clean-up in four communities in Chile and Argentina following the 2015 Calbuco eruption. We evaluate the model outputs both in their accuracy and precision to reproduce the reported values of removal volumes and clean-up operation durations, as well as the relative utility of the modelling results.

3.7.2 Forecasting removal volume

Many factors might be influencing model outputs and need to be considered when forecasting the volume of tephra that requires removal after a tephra fall. These factors include: erosion and compaction of tephra deposits (Blong et al. 2017), affected land use (Hayes et al. 2015), road types (Blake et al. 2017), infiltration into storm water systems (Wardman et al. 2012), quantity of tephra disposed onsite or left in situ and not included in reported volume estimates (e.g., in a garden) (Magill et al. 2013), and uncertainty and error associated with tephra measurements (Engwell et al. 2015; Bonadonna et al. 2015). Below, we discuss each of these factors in the context of the case studies investigated in this work and considerations that future workers should consider if applying the Hayes et al. (2017) conceptual model.

Erodibility of the deposit is an important factor when considering whether tephra is removed from roads across the four case-study communities, in particular the potential for the tephra to become airborne. In Ensenada, tephra deposits were sufficiently coarse (see Table 3.1) and dense to not warrant stabilisation at disposal sites, nor were stabilisation and clean-up efforts undertaken on local gravel roads. In comparison the deposited tephra in JDA was very fine-grained (see Table 3.1) and easily remobilised, which prompted greater clean-up of tephra on gravel/dirt roads in the township. Thus, it appears that when clean-up volumes are to be modelled it is necessary to consider the road surface type that tephra is being deposited on and whether the tephra is likely to become airborne and cause further impacts for the affected community.

Hayes et al. (2015) suggested that land use is an important component of clean-up requirements. Ensenada is considerably different to other case study communities since much of the affected area was farm land. Since we do not know which farms removed tephra and which did not, we assumed that all farms affected removed at least one third of the volume of tephra that fell on their property (refined model). However, some farms did not remove any tephra, which may contribute to the over-estimation. Thus, although similar land use can be affected by the same degree of tephra deposition the response at the individual property level may differ, which can influence model outputs. This is particularly pronounced in the Ensenada case study due to the relatively large land parcel sizes and sparsely distributed population.

Road types can strongly influence the volume of tephra removed following a tephra fall (Hayes et al. 2017). For example, there are many gravel or dirt roads in SMA and JDA from which officials said deposited tephra need not be completely removed. Unfortunately, OSM road data does not include road surface type. We are unsure of the proportion of deposited tephra that fell on dirt roads that was removed, and so do not provide a more refined modelled estimate of tephra removal factoring this in. Modelled tephra clean up volumes estimates were also very high for Ensenada, which similarly has a number of local dirt roads. Our observations during our field visit suggest tephra was only graded to the side of the dirt roads. The model performed comparatively well in JDA despite having only one paved road (Route 40). Thus, the presence of dirt roads may not be the sole factor influencing over-estimation of tephra removal volumes.

Infiltration of tephra into storm water systems can cause localised flooding following a tephra fall (Blong 1984; Wardman et al. 2012; Wilson et al. 2011). An unspecified amount of tephra entered into the storm water system in SMA and was transported directly into Lake Lácar, eventually provoking blockages. Although a small amount of tephra was removed from the storm water system to clear blockages, it is unclear whether tephra removed from the storm water system contributed to the reported estimated removal volume. However, even if this tephra was included in the reported removal volume, it is unlikely this is the sole source of error as the pipes in SMA are small and unlikely to have capacity to hold the sufficient volume of tephra to account for the discrepancy. Thus, tephra entering the SMA storm water system could be a supplementary, but unquantified, reason for the over-estimation of model outputs.

A common strategy of tephra clean-up operations is to remove the bulk tephra and then wash the surfaces. This occurred in each of our case study locations, but information is unavailable to quantify the proportion of tephra that was washed rather than removed. This may partially explain over-estimation of volume removal as some material was not removed, but rather washed to the roadside where it is left to erode. Even after surface washing it is common for a fine coating or residue of tephra to remain in urban areas after official clean-up operations have ceased (e.g., Blake et al. 2015). Another potential source for model over-estimation is that individual property owners may clean up to different standards and/or they may store ash on their own property rather than relying on municipal clean-up. Hayes et al. (2017) indicated that this was a limitation of the approach they undertook for Auckland, New Zealand, and would likely mean modelling outputs are overestimated. We suggest that although these results are promising, more detailed examinations of clean-up efforts from future tephra falls should gather information on the tephra that remains in place after clean-up operations. In particular, direct observation and tracking through a waste management information system would be highly useful (e.g., Brown et al. 2011).

Uncertainty ranges in our analysis are large primarily because of considerable uncertainties associated with tephra thickness measurements. Uncertainty would be less when modelling for pre-eruption impact assessments as it is typical that the model outputs from tephra deposition models provide either uncompacted thickness or loading (g/cm^2), so the modeller can take corrective action to factor in potential deposit compaction. Precise estimates of tephra volume (e.g., 20,000 m^3 compared to 23,000 m^3) are probably unnecessary: order of magnitude estimates are more appropriate (e.g., 20,000 – 40,000 m^3). Although our model outputs appear to overestimate tephra removal for Ensenada and SMA, the estimates are considerably closer to the reported removal volumes than if we assumed that the entire tephra deposit was removed. The model successfully reproduced the removal volumes reported in JDA when using the thresholds from Hayes et al. (2017). Unfortunately, we do not have a reported removal volume for VLA, but the model outputs appear reasonable given that clean-up was reported by officials as being of a much smaller scale than in either SMA and JDA. We consider the quantitative modelling approach undertaken here for estimating tephra removal volumes to be an effective and useful method for pre-event impact and risk assessments and could also be usefully deployed immediately post-eruption as a component of a rapid impact assessment, so long as uncertainties such as those outlined here and Hayes et al. (2017) are appropriately considered.

3.7.3 Forecasting clean-up operation duration

Hayes et al. (2017) suggested that due to a range of factors (e.g., remobilisation, operational inefficiencies, evacuation/exclusion requirements, lack of prior experience), their conceptual approach to clean-up operation duration modelling will likely under-estimate the duration of clean-up. Our findings here do not systematically under-estimate clean-up operation duration, suggesting that the interaction between the above components is not simple. Below we discuss additional insights into clean-up operation duration modelling derived from this work.

The clean-up duration model assumes a constant clean-up rate throughout the clean-up effort (Hayes et al. 2017). However, clean-up operations are dynamic. They often start slowly as impact assessments are undertaken and authorities get a sense of the scale of the problem and resource requirements, and then additional resources arrive, reaching a peak in activity, and then decay for the final phases before returning to business-as-usual levels. This appears to have been the case in JDA, where clean-up operations initially utilised two dump trucks in each of the five clean-up sectors (10 dump trucks in total), but this increased to 50 dump trucks for an unknown duration after the first week. Additionally, analysis of the rate of clean-up using cumulative volumes reported in the media suggest that the average rate throughout the entire clean-up (~1900m^3 per day) is over double the rate removed in the first 6 days of the clean-up operation (~800 m^3 per day). This demonstrates the importance of understanding the temporal dynamics of tephra clean-up operations for more robust model outputs. We suggest spatio-temporal dynamics as an important area of future research not only for tephra clean-up but for general disaster response and recovery efforts.

Our modelled clean-up operation duration estimates for Ensenada appear optimistic (Figure 3.11). A complicating factor for this is that much of the Ensenada economy is based on tourism, and many of the properties are vacation homes. Thus, removal of tephra from some properties took considerably longer because the owners did not return to clean up their properties for months. During our visit to the area 19 months after the eruption, many properties still had tephra. Therefore, we suggest this model for estimating tephra clean-up durations is ill-suited to sparsely populated towns with relatively low levels of permanent occupation.

Hayes et al. (2015) suggested that prior experience with tephra clean-up could be a valuable factor for increasing the efficiency of future clean-up operations, due to having an experienced population and municipal authorities with a clean-up plan that can be utilised in the future. This appears to be partially true for VLA, which had experience cleaning up tephra from the 2011 Cordón Caulle volcanic complex eruption. Inhabitants knew the basics of clean-up and what to expect and potential disposal sites were already identified. However, as the tephra deposition from the Calbuco eruption was considerably less in volume and duration than that of the Cordón Caulle eruption, we cannot draw robust conclusions about whether the response was truly stress-tested. We note that prior experience can also cause problems during clean-up as authorities and/or the population have inappropriate expectations that clean-up will operate in the same manner as previous clean-up operations. SMA found the Calbuco tephra clean-up to be considerably more difficult than the Cordón Caulle tephra fall clean-up. The interview participant stated the 2011 Cordón Caulle tephra fall clean-up experience led them to believe that the storm water system could cope well with tephra ingestion and that this could be used for future tephra clean-up operations. However, during the 2015 Calbuco clean-up, the tephra caused blockages, which they attributed to the finer grainsize, and tephra had to be removed using vacuum trucks. So, while previous experience can be useful, each tephra clean-up needs to consider the wide spectrum of potential characteristics of deposited tephra.

Finally, the model here assumes a single coordinated clean-up operation. Remobilisation of tephra from ‘ash storms may require multiple clean-up efforts to be undertaken over many years (Wilson et al. 2011). The model presented here has not evaluated secondary clean-up efforts that could be required, particularly in JDA where the climate is relatively dry and potential for remobilisation relatively high.

3.8 CONCLUSIONS

Tephra clean-up is a fundamental component of post-eruption response and recovery. Planning for clean-up after volcanic eruptions is necessary for best practice volcanic risk mitigation. Utilising impact and risk assessments is one way to gain useful insights into the clean-up requirements under different eruption scenarios. In this study we have gathered useful insights into the opportunities and challenges associated with using geospatial modelling as a tool for clean-up operation planning by studying the clean-up experiences after the 2015 Calbuco eruption of four communities in Chile and Argentina. Each community experienced differing challenges associated with their clean-up operations and each had differing priorities. We have evaluated the performance of quantitative geospatial tephra clean-up modelling as a method for gaining insights into tephra clean-up requirements. Our results demonstrate that the relatively simplistic geospatial analysis yields credible and usable estimates of tephra volume to be removed and tephra clean-up operation durations. However, it is necessary to consider potential sources of uncertainty across the hazard, exposure, and vulnerability domains. As a priority, we consider it important to iteratively collect information relating to the experiences of communities conducting tephra clean-up operations to fill the gap in empirical information regarding tephra clean-up operations. We have demonstrated potential areas of confusion if data are not collected carefully. As a next step towards greater understanding of tephra clean-up, we suggest that gathering data and analysing the spatial and temporal dynamics of tephra clean-up operations will yield useful information on priorities and demand for resources through a clean-up response. Additionally, other forms of waste can be generated from a variety of volcanic hazards (e.g., construction and demolition, electronics, perishable), yet there is very little information detailing how other types of waste are managed. We suggest more comprehensive analysis of waste management following volcanic eruptions is necessary.

Although we have applied this analysis to select locations in Chile and Argentina, there are many communities around the world that are exposed to future tephra hazards and are not dissimilar to the communities studied in this paper. Our results demonstrate that even with differing contextual components (urban fabric, climate, and resource availability) and the large uncertainties around tephra measurements, estimates of removal volumes and the dynamic aspects of clean-up operations (and the other uncertainties described here), our results demonstrate that our simplistic clean-up model provides useful information. This suggests that this approach for identifying potential clean-up operation requirements is useful as part of pre-event response and recovery planning.

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Chapter 4: Timber-framed Building Damage from Tephra Fall and Lahar: 2015 Calbuco Eruption, Chile

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ABSTRACT

Assessing the damage to buildings from volcanic eruptions is an important aspect of volcanic risk assessment and management. However, there is a limited empirical evidence base to draw upon when describing the relation between volcanic hazard intensity and resulting physical damage. The 2015 subplinian eruption of Calbuco volcano, Chile, caused damage to buildings near the volcano because of tephra fall and lahars. Chilean authorities conducted a damage assessment of 961 properties (990 buildings) to inform an assistance programme for property owners affected by the eruption. Property assessments typically contained observations and classification of damage to a house, and in some instances accessory buildings such as sheds, garages, and exterior storage rooms. In this study we used this unique damage data set to adapt damage state frameworks for tephra fall and lahar for classifying and analysing damage observations. We developed data quality indicators to provide transparency for how we accounted for data quality issues. We assigned a tephra and/or lahar damage state to 571 buildings (530 houses and 41 accessory buildings). The 419 buildings for which we did not assign a damage state either had too little information or fell outside of tephra and/or lahar hazard zones. The minimum tephra thickness isopach band that caused complete collapse was 10 to 15 cm (dry deposit loading ~1 to 1.6 kN m^{-2}, saturated deposit loading 1.6 to 2.4 kN m^{-2}), but most commonly (55% of tephra exposed DS5 houses n = 11), this occurred at 15 to 30 cm (dry deposit loading ~1.5 to 3.3 kN m^{-2}, saturated deposit loading 2.4 to 4.8 kN m^{-2}). Lahar damage was typically described as complete (DS5), with 26 houses being swept away or destroyed around the Blanco South River. Our results add to the limited evidence base of post-eruption tephra and lahar impacts to buildings and contribute to volcanic risk and impact assessment.

4.1 INTRODUCTION

Assessing the impact of volcanic hazards to buildings is an important focus of volcanic risk assessment globally (Bonadonna et al., 2018; Jenkins et al., 2014; Wilson et al., 2014). Post-eruption volcanic impact assessments studying the effects of volcanic eruptions on buildings are useful as they provide valuable insights of observed damage in a real-world environment (e.g., Spence et al., 1996; Blong, 2003a; Baxter et al., 2005; Jenkins et al., 2013; Jenkins et al., 2015a). However, it can be challenging to collect this information due to safety concerns, ethical considerations, rapid alteration of deposits (e.g., by rain or clean-up), as well as technical and logistical challenges (e.g., lack of relevant experts, cost) (Jenkins et al., 2015a). Consequently, there are few studies that have comprehensively assessed volcanic impacts to buildings during or following volcanic eruptions and there is a relatively poor understanding of the susceptibility of buildings to volcanic hazards (Blong, 2003a; Jenkins et al., 2013; Wilson et al., 2014). This hinders the development of more accurate vulnerability models that could be used to assess the likely performance of buildings during future eruptions.

This study analyses the impacts to timber-framed, predominantly residential buildings (houses), from tephra fall and lahars of the April–May 2015 Calbuco eruption, Chile. It adds to the small number of studies in the global literature that comprehensively analyse building damage from volcanic eruptions (e.g., Spence et al., 1996; Blong, 2003a; Baxter et al., 2005; Jenkins et al., 2013; Jenkins et al., 2015a; Jenkins et al., 2017). Our analysis relies upon damage observations, classifications and photos by the Chilean Ministerio de Vivienda y Urbanismo (MINVU) during governmental damage assessments between 29 April and 21 October 2015, and our own observations and semi-structured interview data gathered 19 months post-eruption. We develop a fit-for-purpose damage state framework for categorising damage induced by tephra fall and lahars from the 2015 Calbuco eruption. We characterise uncertainty and challenges associated with hazard, asset, and impact data and discuss future research that could help with these challenges.

In the Background section we present an overview of Calbuco volcano and its 2015 eruption, describing relevant characteristics of the emergency response for the eruption. We summarise typical building characteristics of houses near Calbuco volcano. In the Methods: assessing post-eruption damage section we outline our approach to developing a building damage state framework for volcanic hazards, describe the volcanic and building data used in our analysis, and our approach to assigning damage states. In the Results section we present our findings relating to relationships between hazard intensity and assigned damage states. Finally, in the Discussion section we interpret our results and their implications for damage state framework development, the assignment of damage states, and associated uncertainty with hazard, exposure, and impact data collection.

4.2 BACKGROUND

4.2.1 Calbuco volcano and eruption history

Calbuco volcano (41.33°S, 72.618°W, 1974 m a.s.l.) is a late-Pleistocene to Holocene andesitic volcano located in the Southern Volcanic Zone of Andes mountain range (Stern et al., 2007) between Llanquihue and Chapo lakes to the west side of Liquiñe-Ofqui Fault Zone (López-Escobar et al., 1995). The Southern Volcanic Zone of the Andes (~30 active volcanoes), where Calbuco volcano is situated, results from subduction of the oceanic Nazca plate under the South American plate (Stern et al., 2007; López-Escobar et al., 1995). The volcano has been built over the past 300,000 years, spanning three glacial-interglacial cycles, with andesitic products dominant in the past 100,000 years (Moreno, 1974, 1976). At the beginning of the most recent postglacial period, the main cone collapsed generating a large volcanic avalanche, which flowed to the north, resulting in a 3 km^3 volume deposit covering 60 km^2 (Clavero et al., 2008; López-Escobar et al., 1995). An andesitic dome grew inside the collapse amphitheatre; this has since been the site of several viscous lava flows. Typical volcanic hazards for eruptions of Calbuco volcano include tephra fall, lava flows, lahars, and pyroclastic flows (Figure 4.1; Moreno, 1999; Moreno et al., 2006; Stern et al., 2007). Historical eruptions have impacted agriculture, damaged buildings, and required evacuations (Table 4.1).

4.2.2 Land use, infrastructure, and building typology

Ensenada is the closest village to Calbuco volcano (~15 km NE) with 1169 inhabitants (INE, 2017) and was the most directly affected area in the 2015 eruption, exposed to lahars and tephra fall accumulation. Ensenada is a sparsely populated and spread out community, with most permanent and seasonal residences located along Route 225 (Figure 4.1). The precise boundary of Ensenada is poorly defined; we use the name to refer to the area between Calbuco and Osorno volcanoes that was affected by the 2015 tephra fall. Puerto Montt, the capital of the 'Los Lagos' region, is located 30 km SW of Calbuco volcano (pop. 171,000; INE, 2017); Puerto Varas and Alerce are urban areas located 25 km from the volcano with 29,000 and 46,000 inhabitants respectively (INE, 2017). In the areas surrounding Calbuco volcano, settlements are relatively sparsely populated farming and touristic areas, with denser population concentrations to the north and west of the volcano (Figure 4.1).

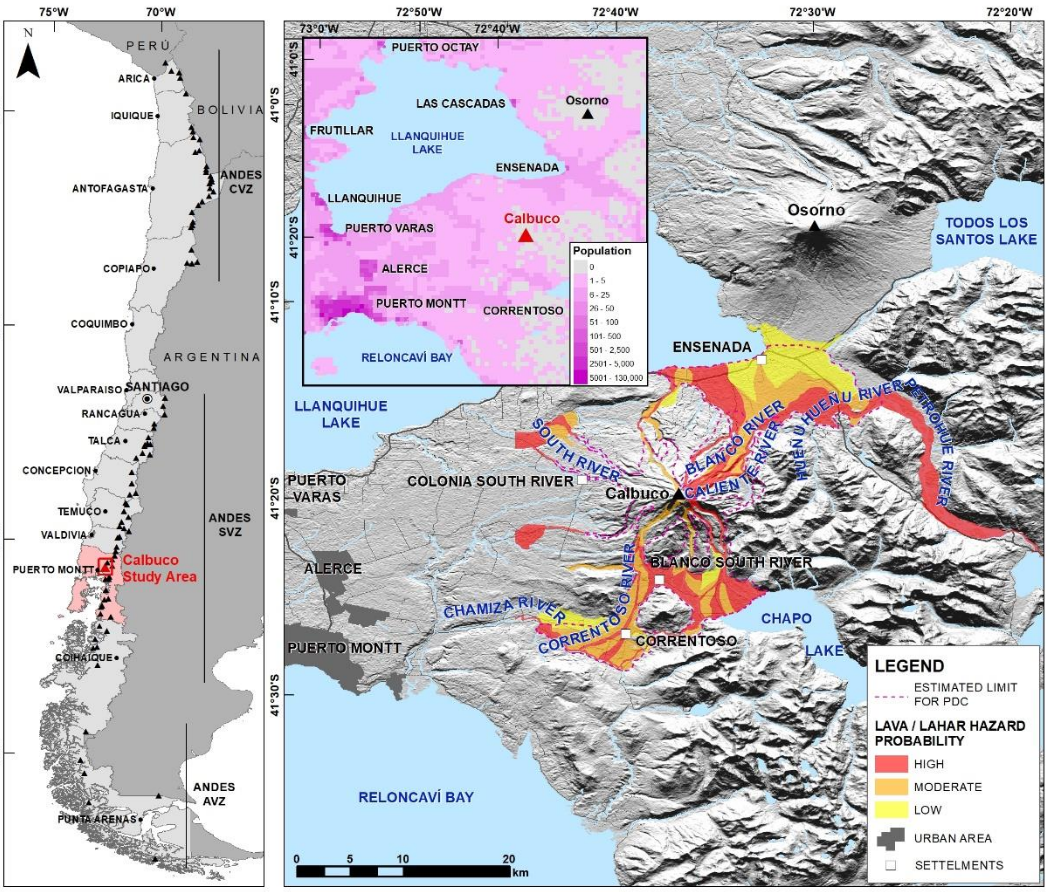

Figure 4.1: Map of the study area, including hazard zoning from Moreno (1999) and population distribution (LandScan, 2009)

4.2.3 Economic activities

Tourism is the main economic activity around Calbuco volcano with around 200,000 visitors annually in Puerto Montt and surrounding areas (Sernatur, 2018). The Llanquihue Lake basin is a popular tourist destination with ~350,000 visitors per year (Sernatur, 2018). Commerce accounts for 35% of total businesses in the region. Other important regional economic activities are transport-communication (11%), agriculture (11%), and manufacturing (9%) (Ministerio de Economía, 2014). These four economic activities employ 46% of workers in the region (Ministerio de Economía, 2014).

4.2.4 Building characteristics

Buildings around Calbuco volcano are predominantly timber framed. The Global Earthquake Model (GEM) Level 3 Building Exposure Model for Chile estimates that in rural areas of Puerto Varas and Puerto Montt, ~95% of all buildings are constructed from timber (92% are of timber construction for the whole Los Lagos region) (Santa María et al., 2017). Houses in the study area are typically owner built, 1 or 2 story stand-alone dwellings (Figure 4.2). Chile has a snow loading code (NCh431-2010) establishing the minimum loads roofs must be designed to withstand depending on the latitude and height above sea level (Instituto Nacional de Normalización (INN), 2010). The minimum snow load in NCH431-2010 for our study area is 0.25 kN m^{-2} (INN, 2010). The Chilean wind load code (NCh432.Of71) requires that structures like those in this study be designed to withstand instantaneous wind speeds consistent with 20 years of wind data at the site (INN, 2000). If this is unavailable, basic pressures of approximately 70–106 kg m^2 (equivalent to ~0.69 to 1.04 kN m^{-2}) for heights above the ground of between 0 and 10 m, but this is dependent on surface roughness, and requires the review and approval from an inspecting authority (INN, 2000). Houses in the area south of Calbuco volcano (e.g., Blanco South River) are typically older and not as well maintained as those in Ensenada (Figure 4.3).

Figure 4.2: Examples of timber-framed houses typical in Ensenada. All were subject to 10 - 20 cm of tephra during the Calbuco eruption. (Photos from our field work November-December 2016).

Figure 4.3: Examples of timber-framed houses typical in Blanco South (Photos: MINVU).

4.3 APRIL-MAY 2015 CALBUCO ERUPTION

The 2015 eruption of Calbuco consisted of three major tephra producing phases: 22 April (18:05–19:35), 23 April (00:54–07:00), and 30 April (13:08–15:00) (Castruccio et al., 2016; Romero et al., 2016; Van Eaton et al., 2016). There was little prior warning of the eruption: the initial phase began 3 h after a seismic swarm was recorded (N220 events, ML b 2.5) began (Valderrama et al., 2015) and no prior ground deformation was observed retrospectively with InSAR (Delgado et al., 2017). The first two phases resulted in 12 cm of coeruptive subsidence 2 km south of the volcano at a source depth of 8–11 km (Delgado et al., 2017). Hundreds of earthquakes were associated with the eruption, the largest reported as ML 3.8 located to the west of Calbuco at 6.3 km depth on 23 April 2015 (Valderrama et al., 2015, 2016; Matoza et al., 2018). Eruption column heights were 14.5–15.5 km a.s.l., 16.9–17.3 km a.s.l., and 3–4 km a.s.l. for phases 1, 2, and 3 respectively (Castruccio et al., 2016; Romero et al., 2016; Van Eaton et al., 2016).

Tephra fall from the eruption was dispersed northeast of Calbuco volcano, with the geographically dispersed community of Ensenada affected by 0.1 to 55 cm of tephra (most of the built-up area was affected by 10–20 cm) (Figure 4.4; Romero et al., 2016; Van Eaton et al., 2016). Romero et al. (2016) reported modal grainsize of tephra in Ensenada as −2ø (4 mm), −1ø (2 mm), and 0ø (1 mm) for individual tephra layers from the eruption with rare lithics (~0.2%). Based on their tephra sampling estimate, the deposit is 80% light brown pumice and 20% high density poorly vesiculated pumice. This was consistent with our own limited field observations. Romero et al. (2016) report an average dry deposit bulk density of 997.3 kg m−3 based on “four fine-grained lapilli samples”. We also collected tephra samples from around Ensenada during field work in December 2016, which yielded higher average bulk density values, and consequently, higher potential tephra loadings (Table 4.2), although this may reflect compaction of the deposits in the intervening 19 months.

Lahars occurred in the rivers on the southern (Blanco South River and Este River), and northern and northeastern (Blanco Este River, Pescado River, and Tepú River) flanks of Calbuco volcano (Figure 4.1). The southern sector experienced both syn- and post-eruptive lahars, while the northern sector only experienced post-eruptive rain-triggered lahars. The volume of lahar deposits was 3.9–4.3 × 10^6 m^3 in Blanco South River and 5.5–5.7 × 10^6 m^3 in Blanco East River (Flores, 2016). The Blanco South lahar had a runout of ~12 km and average velocity of 7.5 m s^{-1} (Bono and Amigo, 2015; Flores, 2016). Bono and Amigo (2015) reported a maximum lahar flow velocity for Blanco South River as 25 m s^{-1}.

Table 4.1: Description and impacts from recent eruptions of Calbuco volcano, Chile. See Figure 4.1 for key place names. The Smithsonian Institution Global Volcanism Program has assigned the 1893–1894 eruption a VEI 4, and the 1929 and 1961 eruptions a VEI 3.

Eruption date	Description	Reference
1893-1895	Impacted agriculture (mainly potato farms) and navigation in Llanquihue Lake by tephra accumulation. Pyroclastic flows reached Chapo Lake and Caliente-Hueñuhueñu River and some lahars impacted buildings on the northeast flank, forcing people to evacuate the area.	Petit-Breuilh (2004)
1929	Debris flows impacted the Caliente-Blanco river basin. The melting of ice by lava flows increased the volume of water in Chapo Lake causing flooding of the Chamiza River, damaging buildings, farms and killing several cattle.	Petit-Breuilh and Moreno (1997)
1961	Large lahars reached farms to the north of the volcano. Lava flows also impacted the north flank (6.8 km runout), and to the south (3.5 km runout). A main highway 6 km south of Ensenada was covered with 1–2 m of lahar deposits from Tepú River. The estimated velocity of this lahar was 5–6 m s^{-1}	Klohn (1963); Petit-Breuilh (2004); Castruccio et al. (2014).

Table 4.2: Average tephra bulk density measurements and potential tephra loading from the 2015 Calbuco eruption.

Bulk density	Bulk density (kg m^{-3})	Loading at 0.1 cm (kN m^{-2})	Loading at 1 cm (kN m^{-2})	Loading at 10 cm (kN m^{-2})	Tephra thickness (cm) at minimum snow load code (0.25 kN m^{-2})
Dry (Romero et al., 2016)	997.3	0.01	0.1	0.98	2.6
Dry (this study)	1115	0.01	0.11	1.09	2.3
Wetted (this study)	1134	0.01	0.11	1.11	2.3
Saturated (this study)	1615	0.02	0.16	1.58	1.6

In response to first (and second) phase of the eruption, a 20 km evacuation zone was implemented, based on the risk of potential pyroclastic density currents (Mella et al., 2016; Hayes et al., 2019). However, four days after phase 1, property and business owners were permitted access to some areas in Ensenada between 08:00–17:00 to collect belongings and clear ash from roofs to prevent damage (Hayes et al., 2019). As more information about the eruption was collected and interpreted and eruptive activity subsided, the evacuation zone was reduced to 10 km 6 weeks after the eruption initiation, allowing much of Ensenada to be reoccupied (Mella et al., 2016; Hayes et al., 2019). However, most of the settlements south of the volcano remained evacuated due to limited evacuation routes and persistent lahar risk (Hayes et al., 2019). By September 2015, five months after the eruption began, the evacuation zone was reduced to within 2.5 km of the summit of the volcano (Figure 4.4; Mella et al., 2016; Hayes et al., 2019), allowing access to all previously settled areas.

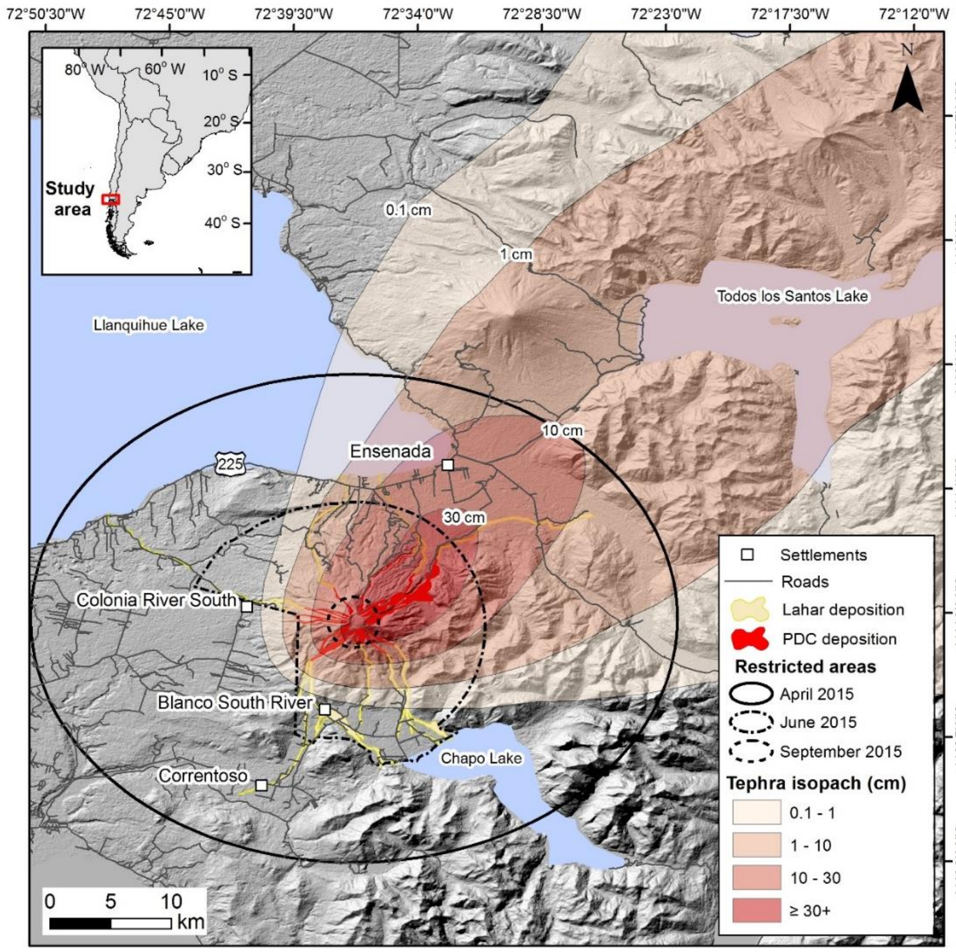

Figure 4.4: Overview of the Calbuco 2015 eruption deposits and evacuation zones. Lahar, PDC, and tephra isopach from SERNAGEOMIN.

MINVU is the agency responsible for providing government assistance to property owners after disasters in Chile. To determine the level of assistance offered, MINVU undertook an extensive field survey of buildings to assess the level of damage sustained at individual properties. This inspection process was used to determine the extent of damage from the eruption, which in turn determined the amount of financial assistance property owners would receive from the Government for repair or rebuilding of damaged houses.

4.4 METHODS: ASSESSING POST-ERUPTION DAMAGE

In natural hazard impact assessment, there are three main approaches to characterising the relation between hazard intensity and resulting physical damage: 1) vulnerability indicators, 2) damage matrices, and 3) fragility or vulnerability functions, including damage ratio functions (Kappes et al., 2012; Wilson et al., 2014). Standard approaches are to quantify the cost of repair/replacement (or a derivative product, damage ratio), or to categorize the damage into building damage states (DS). The former is commonly used in the insurance industry, although in some instances it is mapped from building damage state (e.g., RiskScape; Deligne et al., 2017). Damage states are a type of damage scale that are often used to classify observational post-disaster damage information, ranging from an undamaged to a completely damaged (typically collapsed) state (Blong, 2003b). In this study, we use damage states to characterise damage that occurred to buildings from the 2015 Calbuco eruption. Figure 4.5 outlines the conceptual approach taken in this study and we detail each aspect in the subsections below.

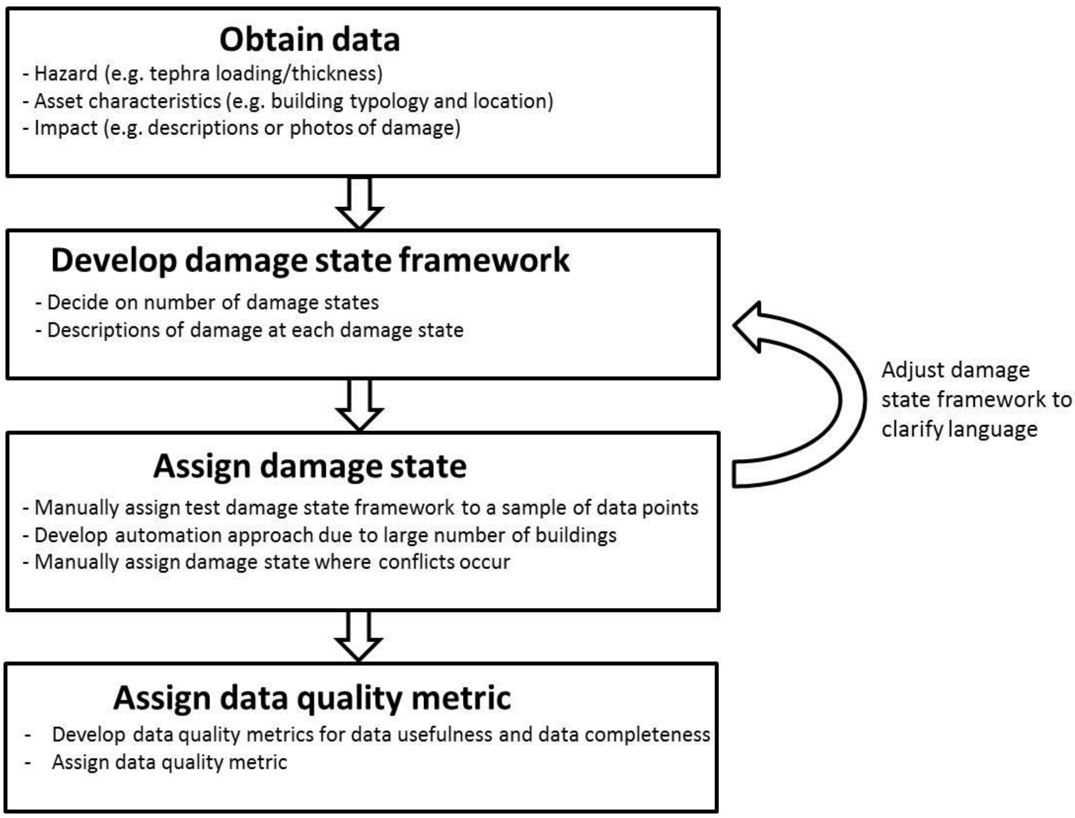

Figure 4.5: Conceptual approach to developing damage state frameworks and assigning damage states and data quality metrics in this study

4.4.1 Existing tephra fall damage state frameworks

In this section, we discuss the tephra fall damage state frameworks used to inform our development of the tephra fall damage state framework used in this study. Spence et al. (1996) undertook the first detailed tephra fall damage assessment, developing and applying damage states to damage resulting from the 1991 Pinatubo eruption in the Philippines, focusing on an area 27 km from the volcano which received ~150–200 mm of tephra. Through analysis of photographs, they remotely assessing 51 buildings and developed the first tephra fall damage state scale, drawing on earthquake building damage state scales (Kárník et al., 1983). Concurrently, Blong and McKee (1995) provided detailed descriptions of tephra fall damage characteristics following the 1994 Rabaul eruption in Papua New Guinea, which produced thick (100 to 950 mm) tephra falls in Rabaul town, ~6–7 km from the vents. They described damage in detail but did not explicitly assign damage states. Blong (2003a) followed up with a survey of 173 Rabaul residential, commercial and industrial buildings (11 different typologies) using field observations and insurance loss data, and categorized damage using a modified version of the Spence et al. (1996) damage states scale. The Blong (2003a) modified damage state considered a wider range of tephra thicknesses and better addressed the economic costs associated with the tephra impact in Rabaul.

Recently there have been further attempts to generate generic building damage assessment frameworks (e.g., Jenkins et al., 2014; Jenkins et al., 2015b) for a range of projects (e.g., MIA-VITA, UNISDR GAR-15) and end-users (e.g., researchers, emergency managers). The lack of empirical observations has been a substantial barrier to their development and validation. This has resulted the use of expert elicitation approaches to develop such frameworks (e.g., Jenkins et al., 2015b). Successful expert elicitation depends on carefully choosing experts, minimizing biased judgements, and the method of reconciling multiple opinions (Cooke, 1991). Blong et al. (2017a) notes that the lack of empirical information has led to considerable variation in expert judgement, which makes volcanic damage assessment frameworks particularly challenging to develop and validate.

4.4.2 Existing lahar damage state frameworks

In this section we outline the lahar damage state frameworks used to develop the lahar damage state framework used in this study. There are fewer damage state frameworks for lahar impacts to buildings than there are for tephra fall (Bonadonna et al., 2018). This may be due to lahar hazards being more localised than tephra fall, the higher risk to investigator safety associated with detailed studies of lahar damage, and/ or because lahar damage to buildings is often total (e.g., swept away, irreparable, and/or burial) or incremental (Künzler et al., 2012; Pierson et al., 2013; Mead et al., 2017). To supplement the paucity of detailed investigation of lahar impacts to buildings, we can look to studies of building impacts from similar flow hazards (e.g., debris flow and flood). The DS0–DS4 damage state framework proposed by Jenkins et al. (2015a) considered observations of building damage collected following a lahar at Merapi in 2011, and damage states developed from observations of building impacts from flood and debris flow. Since Jenkins et al. (2015a) published their framework, two additional sets of damage state frameworks have been proposed by Ettinger et al. (2016) and Kang and Kim (2016) for buildings impacted by flash flood and debris flow hazards, respectively. Both studies propose a five-point scale (DS0–DS4) with damage descriptions closely matching those proposed by Jenkins et al. (2015a).

Ettinger et al.'s (2016) study drew on damage data from 280 buildings in Arequipa, Peru, affected by the 8 February 2013 flash flood event, and the study considered 12 different building typologies. Kang and Kim's (2016) study investigated damage to 25 buildings in Korea affected by 11 debris flow events between July and August 2011. They developed damage states based on the typically observed damage patterns for two broad building typologies: reinforced concrete and nonreinforced concrete buildings.

4.4.3 Data and data preparation

Hazard data

We used hazard data from SERNAGEOMIN (tephra isopach, lahar footprint, PDC footprint) and Van Eaton et al. (2016) (tephra isopach). There are discrepancies between the two tephra isopach maps. The underlying field data used for the Van Eaton et al. (2016) isopachs were collected over two periods: 27–30 April 2015 (5–8 days after the eruption began, and before the final phase), and 13–14 July 2015 (~3 months after the eruption began and after the final phase). The underlying field data for the SERNAGEOMIN map was collected 28–30 April 2015. The underlying raw field measurements used in each of the tephra isopach maps were not made at each building damage observation. This means interpolated maps are necessary to identify hazard intensity for each damage observation. We do not know how interpolation of each map was undertaken. However, we note isopach maps often exhibit differences due to field data uncertainties and/or personal choices and assumptions made by those constructing them (Klawonn et al., 2014; Bonadonna et al., 2015). For this reason, we aggregated the maximum spatial extents of both tephra isopach maps (1 mm fall deposit) and added a 1 km buffer around this maximum extent to delineate our study area. This ensured that all buildings potentially exposed to tephra were included in our assessment. To consistently compare both isopach maps we have combined some tephra thickness bins as per Table 4.3. For lahar, we assign a 100 m buffer to the SERNAGEOMIN footprint account for uncertainty in the precise extent of lahar inundation.

Table 4.3: Tephra thickness bins used in this study and corresponding bins used by SERNAGEOMIN and Van Eaton et al. (2016)

Tephra thickness bins used in this study (cm)	SERNAGEOMIN tephra thickness bins	Van Eaton et al. (2016) tephra thickness bins
0.1 – 1	0.1 – 0.5; 0.5 – 1	0.1 – 1
1 – 10	1 – 2; 2 – 3; 3 – 6; 6 – 10	1 – 2; 2 – 3; 3 – 6; 6 – 10
10 – 20	10 – 15; 15 – 20	10 – 20
20 – 30	20 – 30	20 – 30
30 – 60	30 – 60	30 – 55

Asset and building damage data

The primary damage data source for our study was provided to us by MINVU. These data were collected by MINVU as part of their building damage assessment during and following the Calbuco eruption. Data were collected between 29 April–21 October 2015, and in some instances includes multiple follow-up visits to some properties. According to MINVU, 8–10 assessors worked in the Blanco River/Lake Chapo area, and many more (unknown quantity) conducted assessments in the Ensenada area. MINVU reported that assessments did not take longer than 30 min per house.

We received data in the form of an ESRI shapefile containing 961 points, one for each property surveyed; a property can contain multiple buildings that are either houses or accessory buildings such as sheds, garages, and storage rooms. Where multiple different building types could be identified, we added an additional data entry with the same Observation ID number but with an alphabetical suffix. For example, Observation ID 273 has three instances, the house (Observation ID 273), the greenhouse (Observation ID 273a), and the woodshed (Observation ID 273b). The dataset does not contain highly detailed descriptions of the asset typology (e.g., roof cladding type, roof pitch, floor type) so we relied on broad descriptions of buildings and general classifications of buildings in the study area from GEM (Santa María et al., 2017), validated through field visits and damage photos.

The attribute table provided building owner identifying details, the date of the MINVU building survey, a written description of the building state, and/or numerical indicators developed by MINVU for the level of damage sustained for the entire building (an overall damage classification) (Table 4.4) and individual building elements (Table 4.5). The complete data set is available in the Mendeley Data associated with this manuscript. Table 4.4 provides all available information we have on MINVU damage classifications criteria. We do not know how individual assessors (not identified in the provided data) subjectively considered building elements in Table 4.5 when assigning the final MINVU damage classification – we do not know how much variation may be due to individual assessor practices and biases.

Table 4.4: Damage classification used by MINVU during the Calbuco damage assessment. No further descriptions were available for severity of damage.

Damage classification by MINVU	Severity of damage
0	No damage
1	Increasing degrees of damage
2	
3	
4	
5/6	Severe damage
7	Not verifiable

We exported the attribute table to an Excel spreadsheet, removed building owner identifying details and translated the attribute column headers and building damage written descriptions into English. Guidance was provided from MINVU to clarify some aspects of the data table and collection process.

Table 4.5: Building elements assessed and classified by MINVU during damage assessments after the Calbuco 2015 eruption

Type of building element	**Specific building elements classified by MINVU**
Structural elements	Piles, beams, structural walls, foundation, mezzanine structure, roof.
Construction completions	Windows, doors, roof cover, wall cover, partition walls, ceiling, deck.
Installations	Fresh water, sewerage, electricity, gas.
Exterior to building	Garden fences, perimeter fences, terrain, entry, stairs, gangway, slopes, retaining walls, sanitary networks, spot drain, public power poles.

Secondary data sources utilised in this study were photos, Google StreetView and Google Earth imagery. Most photos we used were provided by MINVU, which were taken by assessors during their visits to the property and were coded using a unique identifying number that linked the observation in the MINVU damage data set and the photo. The remaining MINVU photos supplied were taken during a subsequent visit to a property, and frequently following repairs and clean-up. As a supplementary source of information, we also used photos provided by Ministro Obras Públicas (geolocated), the Puerto Varas municipality, SERNAGEOMIN, our own geolocated photos taken during a visit to the study area 19 months post-eruption, and publicly available media and social media photos we could geolocate. Individual properties were manually linked to the geolocated photos by comparing structures seen in Google Earth aerial imagery with those structures that could be seen in the geolocated photos.

Supplementary photos that did not contain geolocated metadata and/or were from publicly available media and social media were located based on common landmarks that we recognised from our geolocated images and Google StreetView.

Publicly available Google StreetView imagery acquired in March 2013 is available in limited parts of the study area; unfortunately, no StreetView imagery was available for Ensenada at the time of our analysis. Publicly available Google Earth imagery from both before and after the eruption is available for the entire study area. Pre-eruption imagery was taken in January 2014 and post-eruption imagery was taken immediately following the eruption in April 2015 (upper reaches of Blanco South River and in Ensenada), as well as February 2016 (Ensenada) and October 2016 (Blanco South River).

4.4.4 Developing suitable damage state frameworks

We employ a six-point damage state framework (DS0–DS5) for both tephra fall (Table 4.6) and lahars (Table 4.7) as this best represented the spread of damage descriptions within the MINVU data set. Both tephra and lahar damage state frameworks were based on existing frameworks (see Sections 4.4.1 and 4.4.2) and then modified to accommodate damage descriptions within the MINVU data set (Figure 4.6). To identify the necessary modifications, we randomly selected 20 data points and reviewed all available information and agreed on data quality metrics (see Section 4.4.3). Each team member then independently decided on a damage state, which we revealed at the same time by holding up a sign with a number indicative of the damage state. If the vote was unanimous, a damage state was assigned. If there was a disagreement, each team member described their rationale behind the damage state they chose, and we then re-voted. The mean damage state value after the second round of voting - rounded towards the mode if necessary - was then assigned as the damage state. This group voting process allowed us to refine and clarify language and identify assumptions that were being made when applying the damage state scale. To ensure consistency between both frameworks, we added a damage state to the lahar damage state framework of Jenkins et al. (2015a) so that both frameworks use a six-point scale.

Table 4.6: Damage state framework for cataloguing building damage from the Calbuco 2015 tephra falls. A building is assigned a damage state based on the level that best describes the damage, which may not include all of the listed characteristics.

State	Description	Characteristics	Consequence
DS0	No damage	- No damage	
DS1	Minor damage to non-structural elements	- Damage to gutters - Few tiles dislodged - Damage to fittings, e.g., air-conditioning units and appliances - Damage to contents - Dents in the roof covering	- Minor repairs and cleaning necessary
DS2	Moderate damage but vertical structure and roof supports intact	- As above - Bending or excessive (e.g., perforation, cracking) damage (with or without collapse) to up to half of roof covering, e.g., tiles, metal sheet. - Little to no damage to principle roof supports, i.e. rafters or trusses. - Damage to roof overhangs or verandas.	- As above - Interior may require cleaning, repainting, and/or overhaul of electrical systems for habitability and health (e.g., heating and cooking)
DS3	Severe damage to the roof and supports	- As above - Bending or excessive (e.g., perforation, cracking) damage (with or without collapse) to over half of roof covering. - Damage to any single principle roof supports and some damage to walls. - Severe damage or partial collapse of roof overhangs or verandas.	- As above - Building likely unsafe for occupancy
DS4	Partial or total collapse of the roof and supports	- As above - Collapse of roof covering and any single principle roof support(s) - At least half of the external walls and/or internal walls deformed or collapsed.	- Building unsafe for occupancy - Potentially irreversible damage and demolition required
DS5	Building collapse	- As above.	- Building unsafe for occupancy

State	Description	Characteristics	Consequence
		- Collapse of roof, principle roof supports, and/or supporting external walls over more than 50% of floor area of building	- Irreversible damage to most contents and fittings. - Demolition required

Table 4.7: Damage state framework for cataloguing building damage from the Calbuco 2015 lahars. Modified from Jenkins et al. (2015a), with the addition of a new Damage State 1 "Light damage". A building is assigned a damage state based on the level that best describes the damage, which may not include all of the listed characteristics

DS0	**No damage**	- **No damage**	
DS1	Light damage to building exterior only	- Cosmetic damage to/soiling of building exterior. Little to no deposit infiltration into the building	- Clean-up required with minimal damage to building contents
DS2	Minor damage to building	- Deposit infiltration into building under door and through gaps, e.g., ventilation grills	- Damage to building contents
DS3	Moderate damage to building	- Window and door glass failure. Possible weak door and window frame failure	- Damage to building contents
DS4	Severe damage to building	- Loss of parts of external and/or internal wall and infill panels OR - Burial by sediment	- Substantial internal deposits; building likely to be unsafe for occupancy OR - Irreversible damage
DS5	Complete damage to building	- Wall, frame, roof or foundation failure OR - Burial by sediment	- Building unsafe for occupancy; may have to be demolished OR - Irreversible damage or costly clean-up

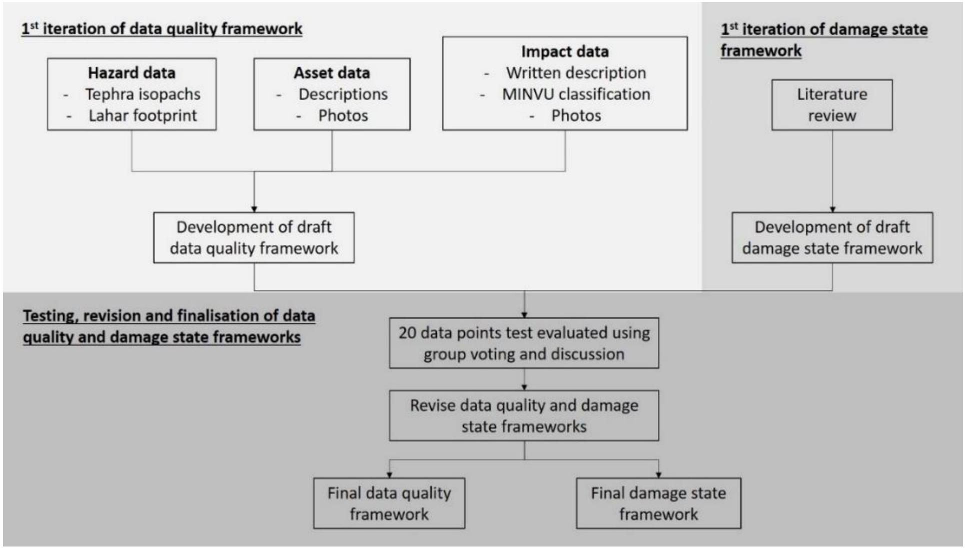

Figure 4.6: Conceptual overview of our approach taken to develop damage state frameworks and data quality metrics (see section 4.4.3) used in this work

4.4.5 Assigning a damage state

We assigned a damage state by manual assignment for a subset of data and used an automatic assignment from an Excel algorithm based on the MINVU damage classification for all data (Figure 4.7). The manual assessment considered all available information and group voting as described in Section 4.4.3. The auto-assignment was undertaken to consistently interpret the MINVU classifications (both the overall and specific elements) in a timely fashion.

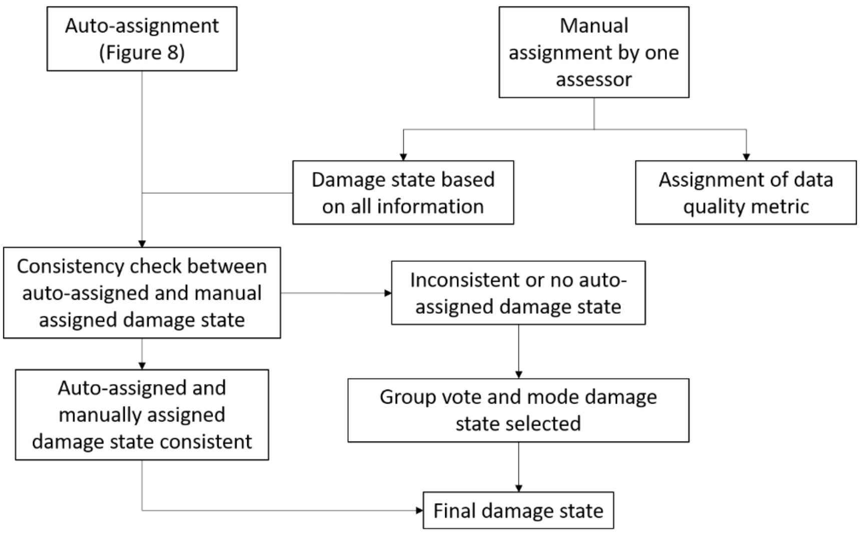

Figure 4.7: Conceptual diagram of our approach to developing a damage state framework and assigning damage states to observations within the MINVU data set.

The auto-assignation of damage states first determined whether the overall MINVU building damage classification was consistent with the classifications made for individual building elements, and that the building was exposed to either tephra or lahar as per the hazard footprints (Figure 4.8). If these conditions were met, and the MINVU overall classification was 1 or 2, then DS0 or DS1 were assigned respectively. It was unclear how higher MINVU classifications (i.e. all individual elements classified as 3, 4, 5, 6) would integrate into our damage state framework, so these were manually reviewed using written observations of damage from MINVU damage assessors and/or any photographs that were available (Figure 4.8). If the first set of conditions were not met, building damage was instead auto-assigned based on the MINVU damage classification of the roof and wall structure (Figure 4.8). If none of these conditions were met, the building was not auto-assigned a damage state.

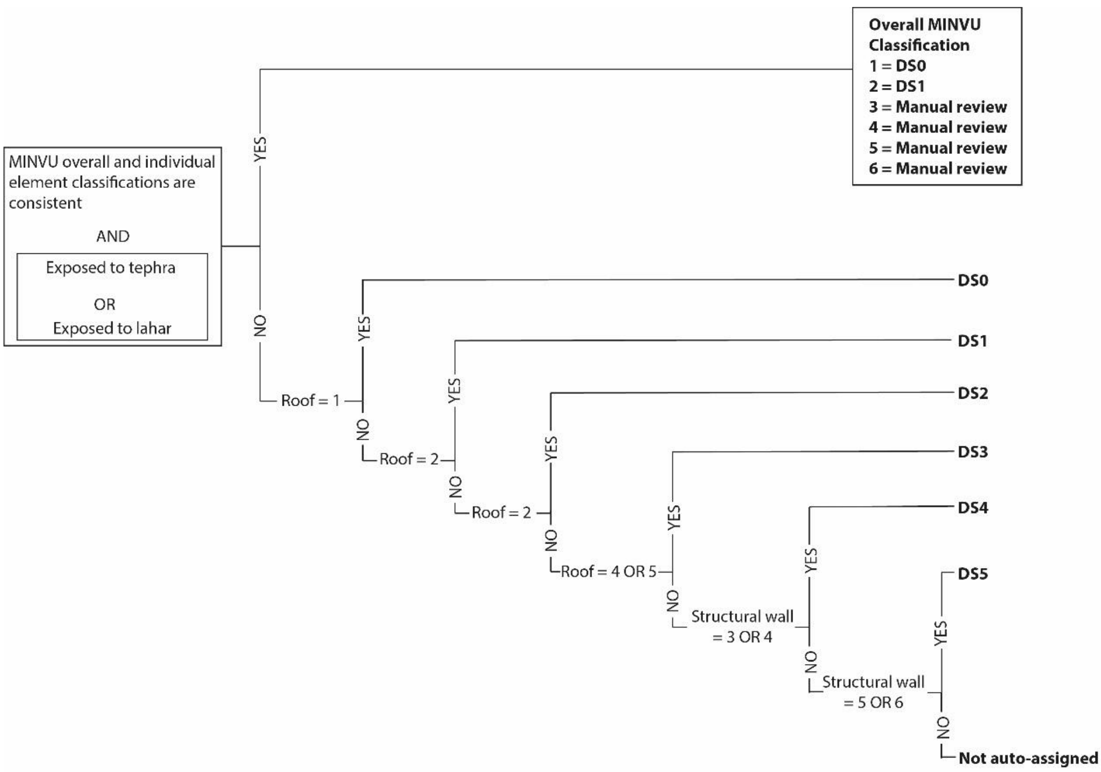

Figure 4.8: Conceptual diagram of the approach used to auto-assign damage states

One co-author (AMM) also worked through the data set and manually assigned a damage state to data points that were exposed to tephra and/or lahar. Manual and auto-assigned damage states were then cross-referenced and checked for consistency.

Where there was a difference between the auto-assigned and manually assigned damage state (n = 147), three additional team members (JLH, RC, GTW) voted on a damage state and the mode damage state from the four team members and the auto-assigned damage state was assigned. Where there was no auto-assigned damage state, we worked in teams of three or more and used written observations to assign the damage state. Observations where a manual damage state could not be assigned were discarded from further analysis.

We decided to err on the side of a higher damage state when there was ambiguity between two or more states. In this instance, the impact data quality rating for usefulness and detail (see section below) was either A or B.

4.4.6 Assigning a data quality metric

Our study relies on three different components of information: hazard (e.g., lahar footprint, tephra thickness), asset information (e.g., building type), and impact of the hazard to the asset (e.g., MINVU observations, classifications, photos). Any given observation may contain considerable data quality variations across hazard, asset, and impact information. Consequently, we have developed data quality indicators, described below.

Data quality indicators

We used data quality indicators to characterise the data usefulness/ detail, and data completeness (Table 4.8). We assigned a data quality metric for hazard, asset, and impact for each data point in the MINVU damage data set based on all available information, resulting in a multidimensional representation of data quality. Data quality metrics were assigned at the same time as manually assigning the damage state. The lowest data quality was assigned to data points that had either no information or no useful information. For some situations it was possible to infer hazard intensity, asset typology, and/or damage state, but there were either conflicting lines of evidence (e.g., different tephra thicknesses on the two isopach maps) or vague descriptions that meant that we could not confirm the hazard, asset, or damage classification. For the hazard intensity component, the distinction between ‘B’ (possible to infer hazard intensity, but potentially conflicting information) or ‘C’ (easy to infer hazard intensity) was whether the tephra information was consistent. A designation of ‘C’ would be a site where the isopach ranges overlapped, for example, a range of 10–20 cm on one isopach and a range of 15–20 cm on the other isopach. Our intention here was to demonstrate relative consistency and not precision. Consistency for the asset and impact categories was determined based on similarities between photographs and written descriptions. Inconsistency was determined if a photo suggested a higher or lower damage state or different asset typology should be assigned than what the written description conveyed.

Table 4.8: Data quality indicators used in our analysis

Data usefulness and detail	Data completeness			
	I **Hazard**: No information **Asset**: No information **Impact**: No information	**II** **Hazard**: Photo OR model(s) **Asset**: Photo OR written description **Impact**: Written observation	**III** **Hazard**: Photo AND model(s) **Asset**: Photo AND written description **Impact**: Photo(s) of damage	**IV** **Hazard**: Local technical measurements **Asset**: Local technical information **Impact**: Written observation AND photo(s) of damage
A **Hazard**: No useful information **Asset**: No useful information **Impact**: No useful information	A-I	A-II	A-III	A-IV
B **Hazard**: Possible to infer hazard intensity AND/OR IF completeness II-IV, conflicting across data sets **Asset**: Possible to infer asset type AND/OR IF completeness II-IV, conflicting across data sets **Impact**: Possible to infer damage state AND/OR IF completeness II-IV,	B-I	B-II	B-III	B-IV

conflicting across data sets				
C **Hazard**: Easy to infer hazard intensity AND IF completeness II-IV, consistent across data sets **Asset**: Easy to infer asset type AND IF completeness II-IV, consistent across data sets **Impact**: Easy to infer damage state AND IF completeness II-IV, consistent across data sets	C-I	C-II	C-III	C-IV
D **Hazard**: Undisturbed hazard intensity measurement taken at the site **Asset**: Engineering level quantitative information **Impact**: Engineering level quantitative information	D-I	D-II	D-III	D-IV

4.5 RESULTS

Below we summarise our analysis of building damage from the Calbuco 2015 eruption. The complete data set is available in the Mendeley Data associated with this manuscript.

4.5.1 Hazard exposure to Calbuco 2015 eruption products

Out of 990 data points, 73 data points were outside both tephra and lahar hazard buffers. Reviewing the written descriptions indicated that 46 explicitly stated no damage from the volcano, 22 had written descriptions that were unclear or contained no useful information, 2 indicated damage from earthquakes, and 3 suggested ash accumulation. We are unable to confirm that ash was definitely present at these 3 locations, but they were 3–4 km from the 1 km buffer we used, suggesting ash accumulation was most likely trace. Given that this information lacks confirmation, we excluded them from further analysis. The remaining 917 data points were located within areas exposed to tephra fallout, lahar, both tephra and lahar, or within the 1 km tephra fall or 100 m lahar buffer zone. The exact number of buildings assumed to be exposed to different accumulations of tephra varied depending on whether the SERNAGEOMIN or Van Eaton et al. (2016) isopach map was used, especially in areas south of the volcano (Figures 4.9–4.10).

4.5.2 Data quality indicators

The distribution of data quality for hazard, asset, and impact information is presented in Figure 4.11. For the hazard component of the data used in this study we had either photographic evidence or a model for all data points (data quality indicator II), and this information was mostly consistent between different sources (e.g., different tephra isopachs) (data quality indicator C: 77%, n = 761). However, there were some conflicts between hazard data (data quality indicator B: 19%, n = 188). Only 4% (n = 41) of data points are complete enough to have both the model and photographic evidence of the hazard (data quality indicator III), and no data points have site specific hazard intensity measurements (data quality indicator IV).

There was very limited information regarding specific asset typology characteristics such as roof pitch or number of stories. Thus, for the purposes of this work we characterised asset typology into two classes: 1) a house, or 2) accessory buildings (e.g., barns, sheds, garages). There was no useful information to determine asset typology in 34% (data quality indicator A: n = 338) of the data set. A photo or written description that indicated the asset typology occurred in 57% of the data points (data quality indicator II, n = 568), compared with 8% that contained both a photo and a written description (data quality indicator B/C-III, n = 84). However, only for 1 of those data points was it easy to infer asset typology (Data quality indicator C). No data points contained engineering level quantitative information (Data quality indicator D).

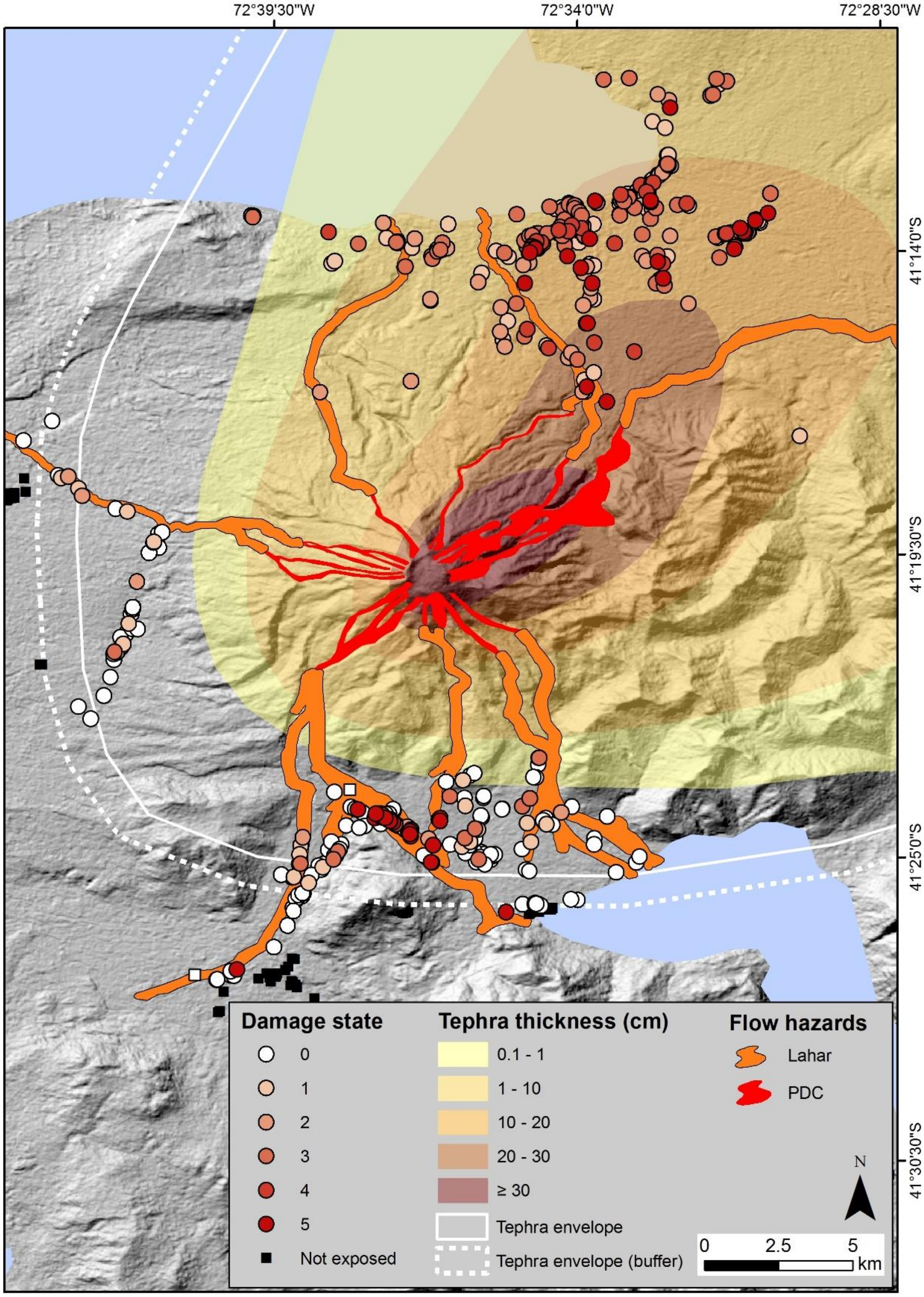

Figure 4.9: Spatial distribution of damage states. Overlaid by the SERNAGEOMIN tephra isopach. Note: for overlapping points the highest damage state is displayed.

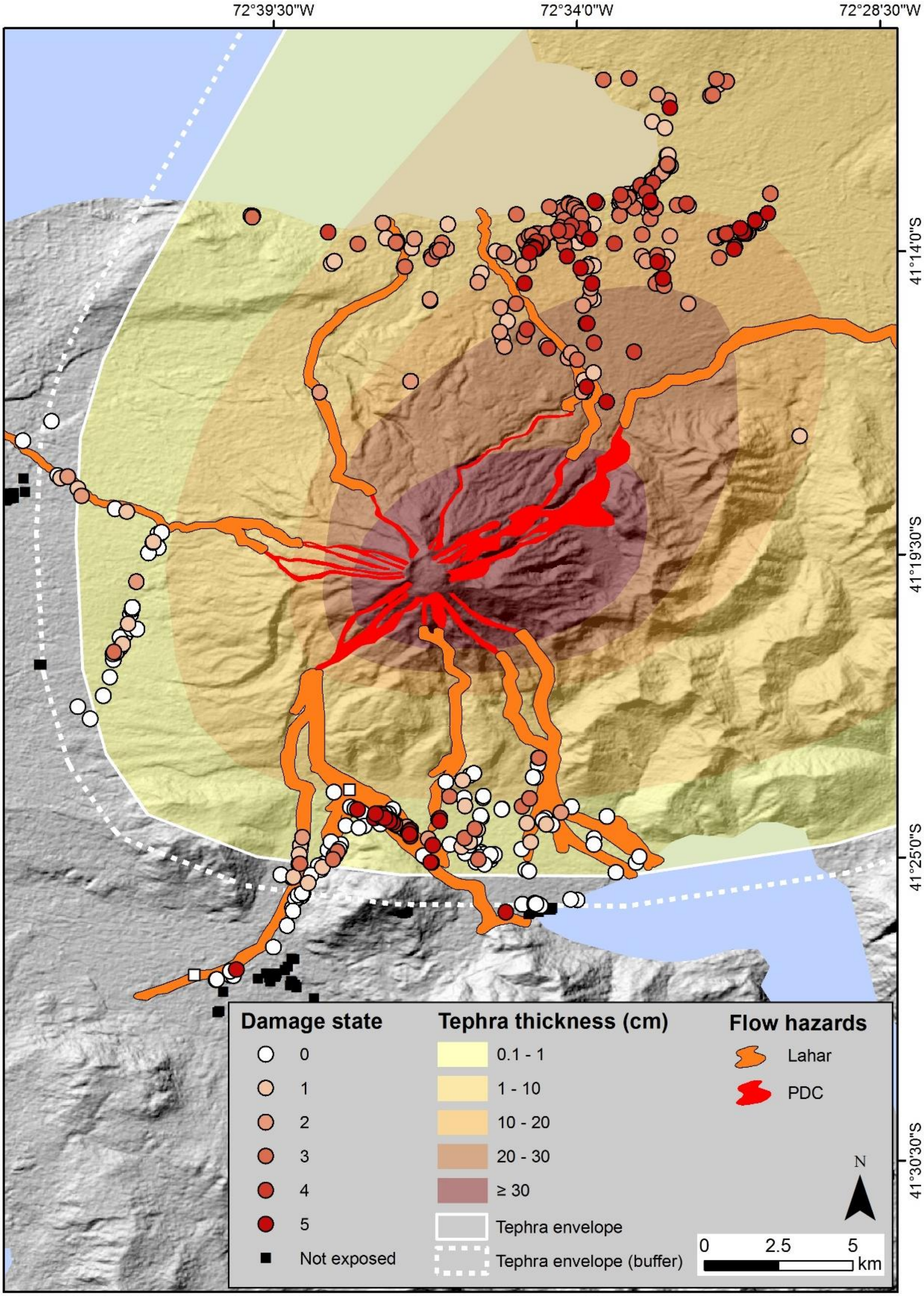

Figure 4.10: Spatial distribution of assigned damage states. Overlaid by the Van Eaton et al. (2016) isopach. Note: for overlapping points the highest damage state is displayed.

Of the complete damage data set (990 observations), 42% of data points had no useful information (data quality indicator A, n = 413). For observations that had only a written description, it was possible to assign a damage state for 33% of data points (data quality indicator B-II, n = 326), and easy to infer a damage state for 24% of data points (data quality indicator C-II, n = 235). There were only 4 data points that did not have a written description but did have a photograph where it was possible or easy to infer a damage state (data quality indicator B/C-III). There were 12 observations that had both a written description and a photo of the damage (data quality indicator B/C-IV).

To summarise, hazard had the highest data quality, with most data points having a data quality indicator of C-II, compared to asset and impact data quality, which mostly fell within the B-II indicator field.

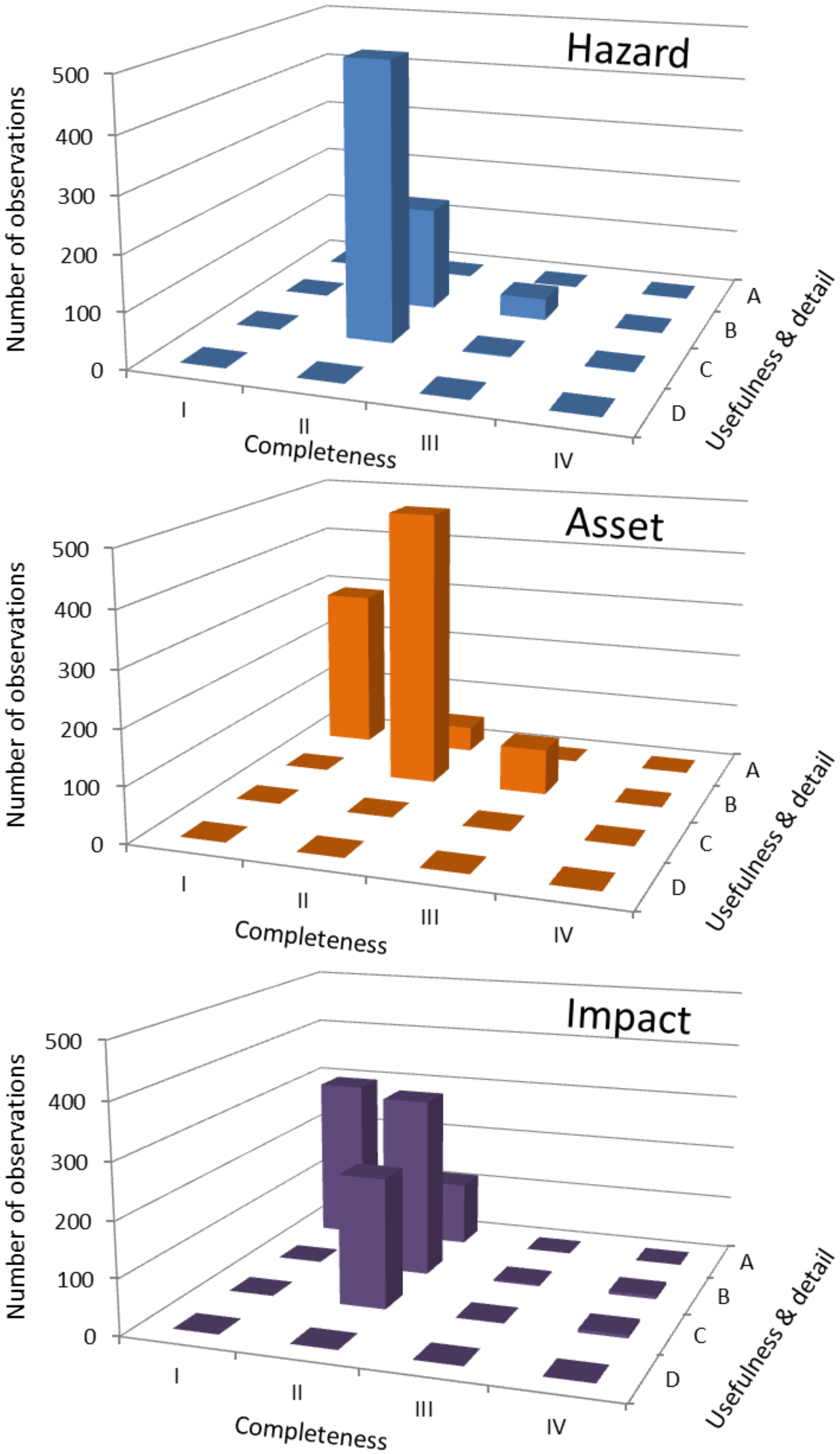

Figure 4.11: Data quality for hazard, asset, and impact information used in this study. The codes are described in Table 4.8.

4.5.3 Damage states summary

Buildings exposed only to tephra fall

More houses were assumed to be exposed only to tephra fall using the Van Eaton et al. (2016) tephra isopachs compared to the SERNAGEOMIN isopachs (Table 4.9). Both yield similar numbers of houses when comparing tephra thickness equal to or in excess of 10 cm (279 for Van Eaton et al. (2016) and 267 for SERNAGEOMIN). A total of 417 houses were classified as exposed to tephra when including the 1 km tephra buffer zone that encompassed the extent of both isopach maps.

Table 4.9: Comparison of the number of houses assumed subjected to tephra using different tephra isopachs

Tephra thickness band	SERNAGEOMIN	Van Eaton et al. (2016)
0.1 – 1	11	38
1 – 10	49	79
10 – 20	211	159
20 – 30	41	96
30 – 60	15	24
Total	327	396

Regardless of the tephra isopach map used, the relationship between damage state and tephra thickness is complicated (Figure 4.12). Half of all houses exposed to low tephra thickness (0.1–1 cm) were classified as DS0. Buildings exposed to over 10 cm of tephra were rarely classified as DS0. Relatively few houses were classified as DS4–DS5 regardless of the tephra isopach or thickness band, indicating lack of widespread structural failure. All houses classified as DS5 were subjected to over 10 cm of tephra. A small proportion of houses that were exposed to 0.1–1 cm of tephra were classified as DS4.

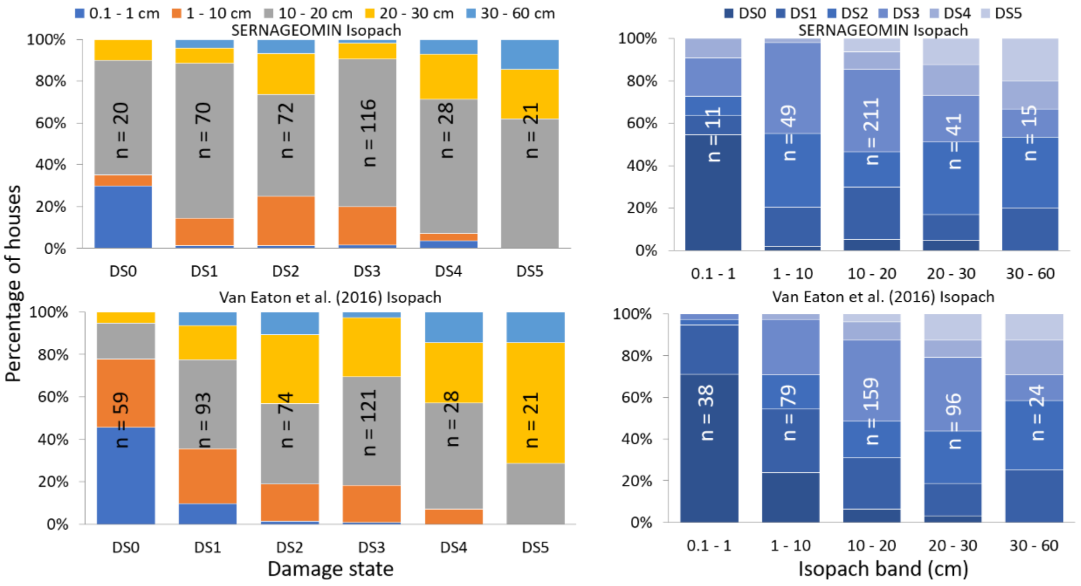

Figure 4.12: Percentage of houses classified by damage state and tephra thickness using two different isopach maps.

In some cases, damage to accessory buildings was described (n = 42). We classified damage to these structures separate from houses as we suspect these structures may not be built to the same standard as houses, which were systematically evaluated by MINVU assessors during the damage assessment. Damage to accessory structures was mostly classified as DS5 (n = 10), but as their structure types were not systematically reported in the MINVU data set, there may be a reporting bias towards heavily damaged structures for these asset types.

Houses exposed only to lahar

Only seven of the 31 houses that were within the lahar zone but not exposed to tephra fall (according to Van Eaton et al. (2016) isopachs) had damage classified as greater than or equal to DS1, compared to 46 of the 95 houses using the SERNAGEOMIN tephra isopach map (Figure 4.13). Most houses (~80%) only exposed to lahars as per the SERNAGEOMIN isopach map are classified as either DS0 or DS5. Substantially less houses were classified DS5 when using the Van Eaton et al. (2016) isopach than were the SERNAGEOMIN isopach, indicative of the broader tephra distribution in the Van Eaton et al. (2016) map that covered heavily affected lahar areas.

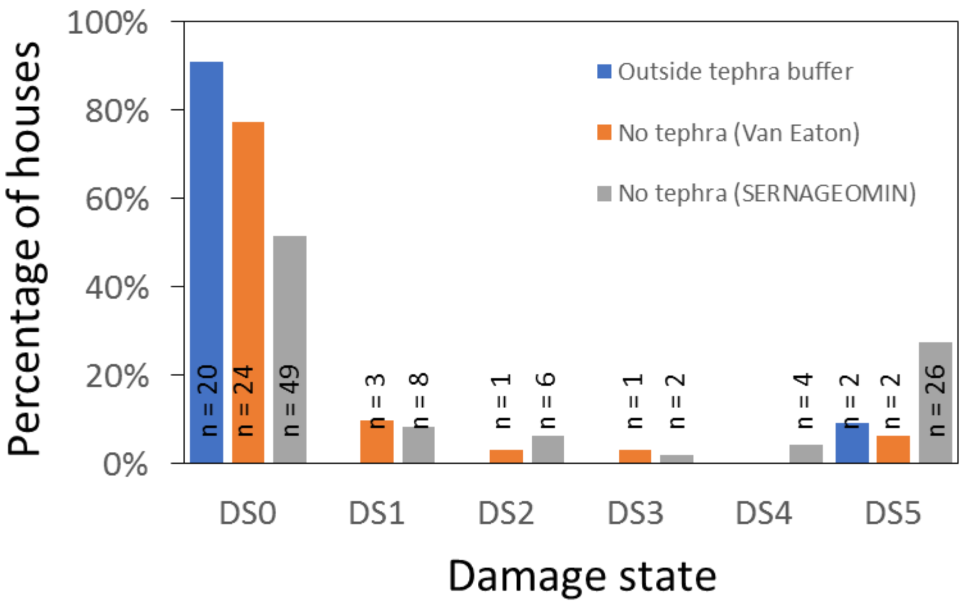

Figure 4.13: Distribution of damage states for houses exposed to only lahar. Note: tephra buffer is 1 km around the tephra extent of both isopach maps (see section 4.4.3)

All but one of the houses that were assigned DS5 and not exposed to tephra fall (according to the SERNAGEOMIN isopachs) were located completely within a lahar zone (i.e. 0 m from lahar). The one house that did not was located 61 m from a lahar zone. The description of damage for this data point suggests that there was a presence of ash (although it also falls outside of our 1 km tephra buffer zone), and that it was a cabin in construction with total loss suffered due to a flood of the river.

For the seven data points assigned DS1 and not exposed to tephra fall (according to the SERNAGEOMIN isopachs), five suggest that tephra fall may have been involved with the damage. Three of these five fall outside of the Van Eaton et al. (2016) isopach map, but within the 1 km buffer zone. The other two fall within the 0.1–1 cm band of the Van Eaton et al. (2016) tephra isopachs. This suggests that either the data points are mislocated or that the maximum extent of tephra fall (including potential remobilisation) is poorly constrained. Photographs, Google satellite imagery, and the written descriptions for the two houses suggest the data points are correctly located, but due to the amount of time elapsed between the eruption and the date the photographs were taken (9 months) it is not possible to conclusively determine the presence of tephra.

Houses exposed to both tephra and lahar

Damage for houses exposed to both tephra fall and lahars indicates dominance towards DS0 and DS5 (Figure 4.14). For the four DS1 assigned houses, the description of damage cannot clearly be attributable to coming from solely lahars or tephra. For the five houses assigned DS2, only two instances described damage attributable to tephra fallout. The remaining three instances describe river sediment inside the house, humidity issues due to the flood waters, deformed doors, broken pipes, and low damage to floor coverings and walls. We assigned DS3 to only one house that was affected by tephra (0.1–1 cm) and lahar, which was reported as having damage to the floor and beams, and damage (severity not reported) to the roof. We assigned DS4 to five houses exposed to tephra (1–10 cm) and lahar, which had either photos or written descriptions indicating lahar sediment ingress, and damage to exterior walls indicative of lahar damage. We classified six houses as DS5 that fall within the 0.1–1 cm tephra thickness band of the Van Eaton et al. (2016) isopach map. For each of these data points, the dominant cause of damage was associated with lahar. The damage descriptions suggest that the house was swept away and/or aerial/ground-based photos show damage clearly caused by lahar activity.

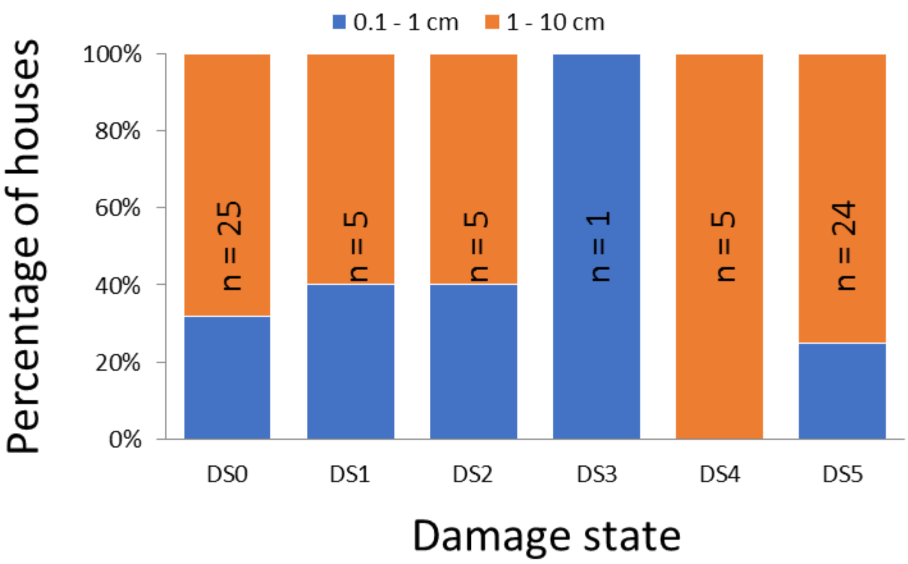

Figure 4.14: Houses exposed to both tephra and lahars at classified damage states. Note: tephra exposure based on Van Eaton et al. (2015) isopachs. No houses were exposed to both tephra and lahars when using the SERNAGEOMIN tephra isopach.

Other descriptions of damage

Although most of the building damage appears to be a result of either tephra fall or lahar, 30 damage observations describe earthquake, land movement, fire/burning, roof perforation, and/or subsidence related impacts. This reflects the multi-peril nature of volcanic eruptions. Subsidence, deformation of walls/windows/doors, and cracks in houses were inferred by assessors as being a result of either earthquakes associated with the eruption or "land movement". There were 14 observations that describe an influx of vermin (rats or mice), which was a concern of public health officials following the eruption (Hayes et al., 2019). One observation (Observation ID 947) described burn marks on the roof cover of a building exposed to 0.1–1 cm of tephra approximately 11 km from the vent. Observation ID 767 described a large "stone" perforating a roof located approximately 7.5 km from the volcano (also down axis of tephra deposition), but there is no indication of the size or mass of the stone. Observation ID 154 described damage that was not repairable, including potentially due to rain water accumulation. It is ambiguous if damage relating to rain water is a compounding effect following damage from the lahars, tephra fall, or whether this is an entirely separate circumstance.

4.6 DISCUSSION

4.6.1 Hazard information for damage assessments

One of the major challenges of post-eruption impact assessment is collecting and using accurate hazard data. There can be a reliance on externally collected hazard information that has been collected for purposes unrelated to damage or impact assessment. The consensual document from the 1st IAVCEI-GVM Workshop "From Volcanic Hazard to Risk Assessment" highlighted the importance of understanding vulnerability parameters to ensure that appropriate and useful hazard data are collected (Bonadonna et al., 2018). Our approach here relies upon tephra thickness and bulk density data collected at varying times after the eruption by different research groups and serves as a useful illustration of the challenges involved with relating hazard data with damage observations. Individual thickness measurements can vary considerably due to local thickness variations (Bonadonna et al., 2015), human factors (Engwell et al., 2013) and post-eruption compaction and preservation issues (Blong et al., 2017b). Measurements are typically interpolated and communicated through tephra isopach maps. As seen in the two maps used in our work, different approaches to contouring tephra thickness data can result in considerable variations in the final isopach map. This presents a challenge when attempting to compare hazard intensity with highly localised impact observations. We also note the variability between the average bulk density measurement reported in Romero et al. (2016), and those we measured (Table 4.2). Our average dry and wet deposit bulk density was approximately 10% higher than the dry deposit bulk density value reported in Romero et al. (2016). The saturated deposit bulk density we report is 38% higher than the average dry bulk density reported in Romero et al. (2016). This variability has an influence on potential tephra loading exerted on buildings and as a consequence increases the uncertainty regarding identifying a potential loading threshold that initiates roof collapse. An important aspect of future impact assessments is to consider all of these issues; ideally, damage assessments should be carried out as soon after impact as is possible and should include site-specific measurements of the hazard intensity (e.g., thickness and load) for each damage data point. However, we recognise that this is very rarely possible due to time constraints, availability of expertise, data collection priorities and safe access to the impacted area (Jenkins et al., 2015b).

For safety, ethical, and logistical reasons, damage assessments are typically undertaken once an event has finished. For volcanic processes, the hazard intensity can increase over time (e.g., tephra deposit thickness increases from further tephra falls or remobilisation, and/or is wetted which increases density), including after catastrophic failure of a structure. This makes it challenging to establish the precise hazard intensity where a given level of damage occurred. Blong (2003a) highlighted this issue when describing damage to structures from the Rabaul 1994 eruption. In some situations, Blong (2003a) was able to use stratigraphic concepts to infer potential collapse thresholds below the final tephra loading measurement. However, these interpretations can take considerable time, which can be highly limited when conducting damage assessments, and require close, and potentially unsafe, inspection of a damaged building. Therefore, a balance must be struck between obtaining detailed building damage descriptions and ensuring that a large enough and representative sample of buildings are studied. Further, some buildings in Rabaul did not collapse until weeks after the load was applied to the roof (Blong, 2003a), which suggests that obtaining a precise threshold of collapse is not only associated with the hazard intensity, but also how long it is subjected to that hazard intensity. As we were reliant on a data set collected by others for different purposes, we were unable to do similarly detailed analysis as described in Blong and McKee (1995) or Blong (2003a). This is an important consideration when interpreting our results and for future post-eruption impact assessments. An additional source of uncertainty regarding tephra load on roofs is the possibility for rainfall to wet the deposits, potentially increasing their load by up to 100% depending on deposit characteristics such as porosity (Macedonio and Costa, 2012). Increased tephra load due to rainfall was a concern for building owners and was one of the reasons for allowing temporary access to Ensenada to clear tephra from roofs four days following the eruption and before any rainfall occurred (Hayes et al., 2019). However, the area has a high incidence of holiday homes and absentee ownership, meaning that some properties may not have been cleaned before rainfall. In fact, tephra could be observed on a few building roofs during our field visit in December 2016. It is not possible for us to establish the buildings in the data set that had roofs cleared of tephra prior to any rainfall.

Remobilisation was not reported to be a major issue in or around Ensenada, which authorities (e.g., emergency managers) considered to be due to the relatively coarse grain size of the tephra deposit (Hayes et al., 2019). As such, post-event remobilisation was unlikely to have considerably affected areas outside of the 1 km buffer zone used in this work. This was not the case farther afield in Argentina, where several communities experienced remobilisation issues (Reckziegel et al., 2016). Thus, it was appropriate to exclude from analysis properties that were outside of the hazard zones for our study of relatively proximal communities. However, for other data sets this assumption may not hold; where our methodology is applied, damage from remobilisation may need to be considered.

It is difficult to determine lahar hazard intensity during post-event impact assessment. Common lahar hazard intensity measures include flow velocity (m s^{-1}), thickness (m) and pressure (kPa), all of which are spatially heterogenous and difficult to measure in the field. Successive lahars can occur post-eruption and cause compounding impacts to exposed buildings. In this work we were unable to find lahar hazard intensity data beyond an estimated average flow velocity of 7.5 m s^{-1} with a potential maximum of 25 m s^{-1} for the Blanco South River (Bono and Amigo, 2015; Flores, 2016). The number of individual lahar events preceding the damage observations made by MINVU is unknown. For this reason, we concentrated on identifying buildings that were subjected to lahar(s) as a result of the eruption. However, even this is not simple as lahar extent was mapped from satellite imagery after the event, meaning the precise extent is unknown (e.g., flood waters with minimal sediment could have affected some areas). For this reason, we applied a 100 m buffer to mapped lahar extents to ensure we captured all buildings potentially subjected to lahar. Consequently, the conclusions that can be drawn from our analysis are limited to general trends.

4.6.2 Asset information for damage assessment

High quality, high resolution, and complete asset data sets are rare across the world because they are expensive to develop and maintain. If accurate asset typology assessments are not made during field evaluations it can be challenging to make comparisons between observed impacts and hazard intensity. Houses in our study area are predominantly timber-framed with metal sheet roofs, which simplified the analysis. However, there is considerable variability in sub-typologies (e.g., roof pitch), construction quality, and building age recorded in the MINVU data set. Although there are occasional references to particularly old or poorly maintained houses, building age does not appear to have been systematically recorded by MINVU assessors, which meant we were unable to conduct further analysis on this characteristic.

4.6.3 Impact information for damage assessment

The recording of impact or damage information in the data set used in this study was variable, which limits the conclusions that can be drawn from the data and subsequent analysis. Ambiguity in the damage descriptions, incomplete information, inconsistent use of terminology, and reporting bias towards severe forms of damage are all potential sources of error in our analysis. An example of an incomplete and vague damage description associated with our analysis can be seen by considering damage observation 704: “The kitchen roof collapsed”. Presented with only this information our group would have assigned DS2 under the assumption that the kitchen is likely to be less than or equal to 50% of the total roof area of a house in the study area, and there is no reporting of damage to principle roof supports. However, upon investigating a photograph of the damage it became apparent that DS4 was appropriate due to clear evidence that a principle roof support beam failed (Figure 4.15).

Figure 4.15: Photo that correlates to damage observation 704 of the MINVU data set. This building falls within the 15-20 cm tephra fall band. Note: clear evidence for failure of principle roof support beam.

Damage described is possibly biased towards the most identifiable damage. For buildings exposed to multiple hazardous processes it can become a challenge to delineate which process caused each damage type. Further, DS1 may not be readily described as it might not necessarily be considered important by damage assessors. Therefore, DS1 might be assigned as DS0 by damage assessors. This demonstrates the importance of understanding the purpose of any damage assessment survey (e.g., life safety, habitability, insurance assessment).

The MINVU data set contained several observations that appear to describe damage that exceeds what might typically be expected for the hazard intensity. This could be an issue with asset classification (e.g., very poor-quality building not captured in the description or photos), vague impact description resulting in an overestimation of damage state (e.g., "damage in the roof"), or inaccurate geolocation of the data point in the field resulting in an incorrect classification of hazard intensity in our analysis.

Our assignment of damage state was based on when the observation was made, which may post-date initial repair undertaken by the property owner. For example, Observation ID 931 reports that the property owners had begun repairing their property. This highlights the perishability of impact data following eruptions: it is important that dates are clearly recorded with damage observations and ideally an indication of whether there is evidence of repairs complete or underway.

Damage that fell outside the scope of the tephra and lahar damage state frameworks in this work was reported in the MINVU damage data set. For example, water damage that occurred after partial roof collapse may have added to the losses experienced by the occupier of that property. There were also several references to infestation of vermin post-eruption. These types of compounding effects are rarely considered as part of volcanic impact or risk assessments, but hazard cascades and compounding effects have been identified as future research requirements in volcanic risk assessment (Bonadonna et al., 2018).

A consistent data recording framework was recommended as a necessary development at the 1st IAVCEI-GVM workshop “From Volcanic Hazard to Risk Assessment” (Bonadonna et al., 2018) to remove subjective terminology and ensure that information is recorded in a consistent and systematic manner. The examples described above and our attempts to manage data quality issues in this study highlight the importance of clear, accurate, and comprehensive records of damage observations for future post-eruption impact assessments. We have not developed such a framework here because damage state frameworks can be highly contextualised due to differing building typologies and standards across the world. Thus, basing such a framework on a single case study would be problematic as it would likely be highly contextualised to the specific issues associated with this case study. Thus, systemic compilation of damage observations from a variety of volcanic contexts would be of use to identify potential data recording requirements.

4.6.4 Considerations for damage states of timber framed houses

An important consideration for volcanic risk assessment is the likelihood of roof collapse due to tephra loading. Our analysis of the MINVU damage data set indicates partial roof collapse of houses may have occurred under dry deposit loadings as low as 0.2 kN m^{-2} (0.6 to 1 kN m^{-2} using Van Eaton isopachs), which is close to the minimum basic snow loading standard of 0.25 kN m^{-2}. These instances were rare, and possibly due to old and poorly maintained buildings, but we cannot rule out that the damage state assigned was a result of our conservative interpretation of damage descriptions. Most typically, partial roof collapse (or greater damage) of houses initiated under minimum loadings of 1.5 to 3.3 kN m^{-2} (dry deposit) or 2.4 to 4.8 kN m^{-2} (saturated deposit), comparable with observations for similar structures made by Blong (2003a) for Rabaul (2 to over 7.5 kN m^{-2}), analytical results from Pomonis (1997) for roofs on Montserrat (1.8 to 3.3 kN m^{-2}), estimates made by Spence et al. (2005) for analogous European buildings (1.8 to 5.5 kN m^{-2}) and for globally similar types in the 2015 Global Assessment of Risk (0.9 to 5.9 kN m^{-2}; Jenkins et al., 2015b). Interestingly, 75 houses in the MINVU damage data set were subjected to loads in excess of 1 to 2 kN m^{-2} and were not assigned a damage state in excess of DS1. The highest loadings that houses in the MINVU damage data set were subjected to were 2.9 to 5.9 kN m^{-2} (dry deposit) or 4.8 to 9.5 (saturated deposit) (n = 15), with a third (n = 5) suffering DS4 or DS5 damage. These houses were all timber-framed with metal sheet roofs, and so not buildings where failure would be unexpected (e.g., reinforced concrete roofs).

Focus of damage states frameworks has often centred on structural performance (e.g., failure of roof support beams). However, defining the difference between DS0 and DS1 is important, as DS1 is usually anticipated as the onset of insurance loss from volcanic tephra fall (Blong et al., 2017c). DS1 is mostly reserved for light non-structural damage (e.g., gutter collapse), but some damage state frameworks identify ‘clean-up required’ as an indicator of DS1. A potential reason for this would be insurance policies that include payment for the costs of clean-up (Hayes et al., 2015). This raises the question of the meaning of ‘clean-up required’ and whether a more precise definition is necessary. For example, if trace tephra fall has occurred, is it appropriate to categorize it in the same damage state as a building that suffers damage to roof covers and gutter failure in addition to a more substantial property clean-up? In our Calbuco study, this would mean that all houses exposed to tephra fall and classified as DS0 would need to be upgraded to DS1. In this case, there would be no ‘DS0’ assignment given hazard exposure, rendering DS0 redundant. The Blong (2003a) damage index included a DS0, but it was not used in their survey as all buildings were exposed to considerable accumulations of tephra. Spence et al. (1996) survey used a DS0 but made no mention of clean-up being required for any of the damage categories used. Thus, the integration of clean-up requirements within residential damage/loss frameworks requires further work. If clean-up is to be included as an indicator of DS1, clear definitions are required as to why it is being used and what ‘clean-up required’ means.

4.7 CONCLUSIONS

The April–May 2015 eruption of Calbuco volcano produced tephra falls and lahars that affected buildings around the volcano. Houses located in and near Ensenada were exposed to up to 30 to 60 cm of tephra deposition (dry deposit loading: 2.9 to 6.6 kN m^{-2}, saturated deposit loading: 4.8 to 9.5 kN m^{-2}). Houses near rivers draining the volcano were exposed to lahars in the aftermath of the eruption. Of a total data set containing 990 damage observations of various building types, we were able to classify building damage for 570. We found that total collapse of houses (DS5) occurred at a minimum tephra thickness of 10 to 20 cm (dry deposit loading: 1.0 to 2.2 kN m^{-2}, saturated deposit loading: 1.6 to 3.2 kN m^{-2}), but there was evidence that partial roof collapse may have occurred to some houses exposed to 2 cm tephra thickness (dry deposit loading: 0.2 kN m^{-2}, saturated deposit loading: 0.3 kN m^{-2}). Damage from lahars was typically characterised as complete (DS5).

Our study demonstrates challenging data quality issues that must be overcome for robust analysis of post-eruption building damage, particularly when reliant on secondary data sources. Most of the data used here were considered to have low indices for data usefulness, detail and completeness. Co-locating hazard intensity and damage observations would reduce much of the uncertainty derived from relating damage to broad measures of hazard intensity. Robust assessment and documentation practices and consistent use of terminology are particularly important to reduce the potential for errors.

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Chapter 5: Developing a Multi-hazard Volcanic Eruption Scenario Suite Using an Interdisciplinary Approach

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ABSTRACT

Understanding future eruptions and their potential consequences is important to aid disaster risk managers to plan for volcanic risk. Suites of scenarios are a useful compromise between data intensive fully probabilistic and subjective fully deterministic (scenario) approaches. In this paper, we demonstrate an interdisciplinary approach that couples stakeholder (volcanologists, risk researchers, policy advisors, infrastructure managers, and emergency managers) requirements with fundamental science to produce multi-hazard eruption scenarios. We apply this approach to the Auckland Volcanic Field (AVF) to develop 8 scenarios ('The DEVORA Scenarios') that cover the wide spectrum of credible eruption phenomena expected from a future AVF eruption. Demand was driven by a desire from stakeholders for scenarios that are scientifically credible and relevant for disaster risk management purposes, including evacuation, welfare, and critical infrastructure disruption planning. Scenarios begin with unrest sequences, followed by eruption sequences of a variety of eruption styles, hazards, volumes, and durations. Stakeholders were embedded throughout the scenario development process, importantly at scoping and design stage and through multiple formal and informal review cycles. The result is a suite of eruption scenarios that are socialised, flexible, and cover the broad range of eruption phenomena likely in a future AVF eruption. We found that balancing scientific credibility with ensuring the scenarios remained relevant and legitimate to stakeholders a challenge that required considerable time and stakeholder consultation. Although this was a hard and time-consuming task, we consider the process of scenario development to be just as useful as the final product: it facilitated open discourse on major scientific uncertainties and information gaps on AVF volcanism, hazards, and risk. This served two important ends: 1) it allowed scientists to communicate areas of uncertainty to other stakeholders such as emergency managers, and 2) it identified potential future research avenues with an obvious and tangible societal benefit. It is anticipated that the DEVORA Scenarios will serve as a foundation for studies exploring the societal ramifications of a future AVF eruption. The process we outline here can be followed to develop credible and relevant suites of eruption scenarios for disaster risk management purposes.

5.1 INTRODUCTION

Preparing for, responding to, and managing the recovery following a volcanic eruption is difficult. To do so, emergency managers, government officials, community planners, politicians, and similar stakeholders are reliant on relevant, credible, and legitimate information (Peterson 1988; Aspinall et al. 2003; Marzocchi et al. 2012; Donovan and Oppenheimer 2014; Leonard et al. 2014). Providing relevant information necessitates information providers who are sensitive to the information demands of the stakeholder (McNie 2007). Information demands not only relate to the specific content, but also timeliness of information provision (McNie 2007). Information must also be perceived to be credible and dependable. Credibility can be built by ensuring that the quality, validity, and scientific adequacy is perceived to be high, which is typically conducted through collaborative research methodologies and peer review (McNie 2007; GFDRR 2014). Legitimacy is: 1) ensuring that those that produce the work are perceived to be free of bias and inclusive, 2) that transparent processes have been undertaken to produce the information and 3) that mutual trust and respect exists between the producer(s) and user(s) of the information (McNie 2007). Each of relevance, credibility, and legitimacy must be carefully balanced (Cash and Clark 2001; Guston 2001; Cash et al. 2002, 2003; Cash and Buizer 2005; McNie 2007; Sarkki et al. 2014).

Probabilistic hazard assessment (PHA) attempts to address the challenges associated with volcanic hazard assessment by evaluating uncertainties through the utilisation of probability distributions (Sparks et al. 2013). However, fully probabilistic approaches often require intensive characterisation of parameters within the analysis. When undertaken for volcanoes that have low quality and/or insufficient data available it can result in different estimates depending on the method used, and so careful performance validation of the approach is required (Beguería 2006). Probabilistic hazard assessment is also challenging to conduct in settings where many interacting hazards are likely to occur in relatively close proximity (e.g., volcanic fields), in part because most existing volcanic hazard models are designed specifically for a single volcanic hazard, and sometimes for a specific volcanic system, making integration of multiple hazard models in a fully probabilistic manner complicated and computationally expensive (e.g., Neri et al. 2008; Zuccaro et al. 2008; Zuccaro and De Gregorio 2013; Jones et al. 2015; Mead et al. 2016; Mead and Magill 2017; Tierz et al. 2017). Thus, in volcanology, PHA is typically used for transparent forecasting and decision making in volcanic crises (Newhall and Hoblitt 2002; Woo 2008), quantitative loss modelling purposes for specific hazards (Magill et al. 2006; Neri et al. 2008) and defining long term hazard zones (Iverson et al. 1998; Sparks et al. 2013). Limited empirical observations of volcanic impacts have so far limited the sophistication of vulnerability models for volcanic hazards, which can undermine the intensive effort required for robust PHA when conducting risk or impact analysis (Wilson et al. 2014; Jenkins et al. 2015).

Deterministic (scenario) hazard assessment (DHA) approaches on the other hand fix input parameters, so are simpler to design and easier to integrate for use in complex systems, especially in data poor contexts. Thus, the resulting output of DHA is often of greater utility for pre-event or strategic planning (e.g., Schoemaker 1995; Bommer 2002; Sonnek et al. 2017), and training purposes (e.g., Alexander 2000; Brunsdon and Park 2009). In a volcanic context, DHA more easily allows for consideration of potential spatio-temporal evolution of a potential future volcanic event compared to PHA (e.g., Blake et al. 2017; Deligne et al. 2017a; Sonnek et al. 2017), both of which are important elements to illustrate the inherent complexity of volcanic eruption-triggered disasters. However, a limitation of DHA is that they are often subjective and focus on developing a single scenario (typically 'worst-case', 'most typical', or 'well known' events), which limits users considering the full range of potential outcomes that may be possible. Hence, the use of a fully probabilistic or a fully deterministic approach depends on the context of the project that is being conducted (Bommer 2002).

In light of the respective challenges associated with each approach, ensembles or suites of scientifically robust scenarios intended to cover a broad spectrum of potential events that may occur and have the potential to drive decision making have been utilised in a variety of applications, such as climate change (Hallegatte 2009), hurricane risk assessment (Ranger and Niehörster 2012), multi-risk analysis (Schmidt et al. 2011), seismic risk analysis (Robinson et al. 2018) and water resource planning (Groves and Lempert 2007). Thus, suites of scenarios act as a middle ground between fully probabilistic and fully deterministic approaches and allows for more flexibility at balancing scientific credibility and relevance for stakeholders.

In this contribution we describe the interdisciplinary approach undertaken to construct a suite of multi-hazard volcanic eruption scenarios ('The DEVORA

Scenarios'), where there is no useful historical record. The DEVORA Scenarios were developed for use in a variety of disaster risk reduction activities related to the Auckland Volcanic Field (AVF). The scenario development process was driven by stakeholder requirements (e.g., evacuation modelling, economic loss modelling) to ensure the outputs were as useful and useable as possible. The scenarios are intended to also directly inform the future development of probabilistic scenario ensembles that will investigate spatial sensitivity of vent location on societal impacts in the AVF. In the next section we provide a brief overview of our study area: Auckland, New Zealand. We then discuss the interdisciplinary approach undertaken to construct multi-hazard eruption scenarios, focussing on decisions that were made throughout the process and the rationale for making them, and stressing that this approach is transferable to other volcanic challenges. Finally, we discuss the benefits and challenges associated with the approach taken in this study and areas that require further consideration.

5.2 SCENARIO PLANNING

5.2.1 Scenario planning for disaster risk reduction

Scenarios are credible, probable, or possible representations of potential futures, but not predictions or forecasts of the future (Bloom and Menefee 1994). Scenario planning makes use of scenarios to identify important planning requirements that need to be considered and has been used across numerous disciplines such as environmental management (e.g. Wodak & Neale 2015; Butler et al. 2016) and disaster risk management (Alexander 2000). Scenarios also allow the integration of dynamic social, political, economic, cultural, and natural processes, which has meant they have proven useful in disaster risk reduction (Bloom and Menefee 1994; Moats et al. 2008; Davies and Davies 2018). The scenario planning process helps develop institutional learning, improved decision-making processes, and identification of new or emerging challenges that may arise during a disaster response or recovery (van der Heijden 1997; Moats et al. 2008; Chermack 2004). Institutional learning is facilitated through scenario planning because it provides a means of dialogue between participants, which help reveal the mental models of participants and identify mutual understandings of complex and uncertain systems that are characteristic of a disaster (van der Heijden

1997; Chermack et al. 2006; Keough and Shanahan 2008; Doyle et al. 2011; Sword-Daniels 2016). This dialogue is important for facilitating disaster research programmes that are integrated with the needs to agencies responsible for managing disasters (Beaven et al. 2016). Thus, as a communication and collaborative tool, scenarios and the scenario planning process helps foster openness to different perspectives, aid in understanding complexity, and give meaning to events through storytelling, which helps make the information contained within memorable and more likely to be acted upon (Chermack 2004; Doyle et al. 2011). From this perspective, scenario planning reduces the cost of knowledge transfer and aids in more effective and efficient decision-making (Chermack 2004).

Due to different contextual environments (e.g. cultural norms, project objectives) there are a variety of models and variations on the scenario planning process (e.g. Schoemaker 1993; Schwartz 1996; Wilson and Ralston 2006; Avin 2007), but most have common elements (Keough and Shanahan 2008; Moats et al. 2008; Amer et al. 2013). Broadly, these elements include: 1) developing an environment conducive for scenario planning, 2) conducting analysis to build a picture of the scenario planning requirements, 3) create scenarios, and 4) use the scenarios.

Developing an environment conducive for scenario planning includes consideration of issues such recognising the need for scenario planning, outlining project objectives and scope, and identifying relevant stakeholders (Keough and Shanahan 2008; Moats et al. 2008). Recognising the need for scenario planning requires an organisational culture that is conducive to the participatory requirements of scenario planning, but some may not be well equipped to make use of scenario planning. Support and leadership from senior managers are necessary for scenario planning because the approach requires acceptance that they cannot predict the future. Determining project scope/objectives and identifying relevant stakeholders that must be included is critical to ensure that the scenarios are useful for their intended purpose. Best practice suggests that teams should be made up of a wide variety of participants with differing intellectual and cultural backgrounds to ensure that the scenarios cover necessary breadth and detail (Schwartz 1996; Davies et al. 2005; Keough and Shanahan 2008).

A coherent picture of the scenario planning requirements must then be built. This requires: 1) collecting necessary data, 2) identifying and conducting detailed research on critical drivers, key issues, and forces of the futures, 3) analysing issues of uncertainty/variability and 4) obtaining an envelope of uncertainty that the scenarios must cover, which will inform how many scenarios must be developed. Once this information is obtained, creation of the scenarios can commence by the scenario building team (Keough and Shanahan 2008). The specific approach and tools used to develop the scenarios will depend on the context of the work being conducted (Bloom and Menefee 1994). Finally, the scenarios are then used to evaluate necessary planning requirements.

5.2.2 Scenario planning for volcanic risk management

Eruption scenarios can come in a range of formats such as event narratives (Johnston et al. 1997; Galderisi et al. 2011), scenarios of specific eruption phenomena (Macedonio et al. 2008), or integrated multi-hazard scenarios (Zuccaro et al. 2008). Event narratives are often qualitative or semi-quantitative and primarily describe the context, conditions, and/or sequence of events that occurs in a given scenario and are often used for tabletop exercises (Sonnek et al. 2017). Scenarios describing specific eruption phenomena, such as tephra fall or lahar, are often used to conduct detailed hazard analysis (Macedonio et al. 2008). Multi-hazard scenarios are increasingly becoming more important in a volcanic risk assessment context due to the inherent multi-hazard nature of volcanic eruptions and potential hazard cascades and compounding impacts that can influence decision making (Zuccaro et al. 2008; Deligne et al. 2017a). The context, intended purpose, and methodological approach that underpin the development of such scenarios is critical to informing their applicability and usefulness.

The data that scientists use to inform volcanic hazard scenario assessments include: 1) the historical and instrumental record, 2) geological interpretations, and 3) analogue volcanoes. Historical data refers to the written record (e.g., Rosi and Santacroce 1984; Thordarson and Larsen 2007; Hutchison et al. 2016; Pyle et al. 2018), whereas instrumental data are quantitative measurements made using field and remote devices (e.g., Lavigne et al. 2000; Palister and McNutt 2015; Newhall et al. 2017). Oral traditions are not often considered part of the historical record but can provide valuable supplementary information (e.g., Lowe et al. 2002; Cronin et al. 2004; Cashman and Cronin 2008; Swanson 2008; Németh and Cronin 2009); we will not discuss these further here. Geological interpretations are possibly the most widely utilised data and include studies that use one of, or a combination of: field, remotely sensed, geochemical, and geophysical data to make interpretations regarding the characteristics of volcanic hazards (Tilling 1989). Information from analogues can be gathered from conceptually similar volcanic settings to characterise volcanic hazards (e.g., Marzocchi et al. 2004; Mastin et al. 2009; Jenkins et al. 2012). Ideally scientists would draw upon all these sources when assessing volcanic hazard, but that is often impractical or impossible (Donovan et al. 2012; Marzocchi et al. 2012). For example, some localities may be data poor on geological information due to limited scientific investigations but have useful historical information that can be drawn on, and with consideration of international analogues useful volcanic hazard information can be derived (Pyle 2018). Thus, it can be challenging for scientists to find approaches that balance credibility in hazard assessments along with providing stakeholders with usable information.

In volcanic impact and risk assessment, it has been common practice — though not necessarily best practice — to take a phenomena-centric approach, where eruption scenarios have comprehensive consideration of the physical eruption phenomena, sometimes with high degrees of precision, and then have impact scenarios 'retrofitted' to them through the addition of exposure and vulnerability components (e.g., asset databases, fragility curves, and impact thresholds). However, the phenomena-centric approach can lack adequate consideration of the information requirements of subsequent users of hazard information (Newhall 1982; Fiske 1984; Ronan et al. 2000; Fearnley 2013; Christie et al. 2015; Fearnley and Beaven 2018; Bretton et al. 2018a, b). This means that work can be of limited use to other users if it fails to address relevant questions or incorporate stakeholder participation (National Research Council 1996; Donovan and Oppenheimer 2014; GFDRR 2014; Bretton et al. 2018a, b). An effective way to manage these issues is through interdisciplinary research methods that integrate concepts and research strategies from multiple disciplines (Barclay et al. 2008; Jenkins et al. 2013; Hicks et al. 2014; del Marmol et al. 2017). Hence, in order to develop robust and fit for purpose volcanic eruption scenarios that can be used for scenario planning, it is necessary to take an interdisciplinary approach that focuses on utilising credible science and user requirements as equally critical and complementary components of the scenario development process.

To manage a volcanic eruption, stakeholders must grapple with the inherent technical complexity of volcanism, the effect it has on society, and the needs of end-users (Doyle et al. 2014; Doyle et al. 2015; Donovan 2019; Doyle et al. 2019). Diverse data types and sources must be collected and interpreted using a variety of techniques and approaches. For example, geochemical analysis is required pre-eruption to determine potential ascent rates of magma (e.g. Brenna et al. 2018), which is important to determine potential warning times from the time magma ascent is detected (e.g. via interpreting seismic data). To determine the potential hazard intensity of volcanic hazards requires consideration of physical volcanological data (e.g. analysis of tephra deposit characteristics), numerical/analytical modelling, and/or consideration of analogues. This information must then be carefully packaged and communicated to those that must make organisation, policy, or operational decisions (e.g. when, who, and where to evacuate). From this perspective, scenarios used in scenario planning act as an effective boundary object between the typical domain of scientists and decision-makers. Thus, an interdisciplinary approach is necessary. Much has been made about the theoretical need for an interdisciplinary approach, but there has been much less consideration of how such an approach works in practice (Hicks et al. 2014). Below, we describe the approach used to develop eruption scenarios in Auckland, New Zealand and how interdisciplinarity can be incorporated within the process.

5.3 CASE STUDY

5.3.1 Background: Auckland, New Zealand

Socio-economic background of Auckland, New Zealand

The city of Auckland currently houses a permanent population of 1.7 million (most within central Auckland: Figure 5.1), approximately one third of the total New Zealand population. Population growth for 2017 was 2.6%, making it one of New Zealand's fastest growing population centres (Stats NZ Tatauranga Aotearoa 2017a). Auckland is a key economic centre, contributing 37.5% to New Zealand's Gross Domestic Product (GDP) (Stats NZ Tatauranga Aotearoa 2017b) and is the base for facilities of national significance. For example, Auckland Airport, located in South Auckland, has approximately 500,000 international passenger arrivals during peak months (December and January), and 75% of the total international passenger arrivals into

New Zealand enter the country through Auckland Airport (Auckland Airport 2018a, b). In 2017 alone, approximately 20.5 million passengers (international and domestic), NZ$6.8 billion of exports (~12% of total New Zealand exports), and NZ$11.8 billion of imports (~21% of total New Zealand imports) passed through the airport (Auckland Airport 2018a, b; Stats NZ Tatauranga Aotearoa. 2018). Auckland seaport located in Waitematā Harbour had NZ$6 billion of exports (~11% of total New Zealand exports) and NZ$22.8 billion imports (~40% of total New Zealand imports) pass through it in 2017 (Stats NZ Tatauranga Aotearoa. 2018). The national electricity grid goes through Auckland and there is no redundancy. If electricity transmission is disrupted in Auckland, no electricity with be transmitted north of Auckland (Deligne et al. 2017a). Thus, disruption to Auckland's urban functionality can be nationally significant.

Volcanology of the Auckland Volcanic Field

Auckland is built upon the Auckland Volcanic Field (AVF) (Figure 5.1). The AVF is a 360 km^2 intraplate volcanic field that has been active for approximately 200,000 years (Searle 1964; Kermode 1992; Allen and Smith 1994; Hayward et al. 2011; Runge et al. 2015; Leonard et al. 2017). Most of the 53 identified eruptions within the AVF have dense rock equivalent (DRE) volumes between 0.001 and 0.03 km^3; only two eruptions have eruptive volumes > 0.1 km^3 (Kereszturi et al. 2013; Leonard et al. 2017). The most recent, and largest, eruption within the AVF was ca. 550 BP at Rangitoto Island (Needham et al. 2011; Kereszturi et al. 2013; Leonard et al. 2017). The geologic record indicates that AVF eruptions can be 'wet' (phreatomagmatic), 'dry' (magmatic), or both, and locally variable environmental conditions play an important role in their occurrence (Allen and Smith 1994; Agustín-Flores et al. 2014, 2015a; Kereszturi et al. 2014). This has implications for the types of volcanic hazards, that may occur during a future AVF eruption (Allen and Smith 1994; Németh et al. 2012; Kereszturi et al. 2014). The location of the AVF vent is unknown (Searle 1964; Bebbington and Cronin 2011; Leonard et al. 2017). Consequently, anywhere within the 360 km^2 area field is treated as a potential site for the next AVF eruption from a risk management perspective (Lindsay et al. 2010; Leonard et al. 2017). Thus, foreseeing the potential impacts from a future AVF eruption is complex.

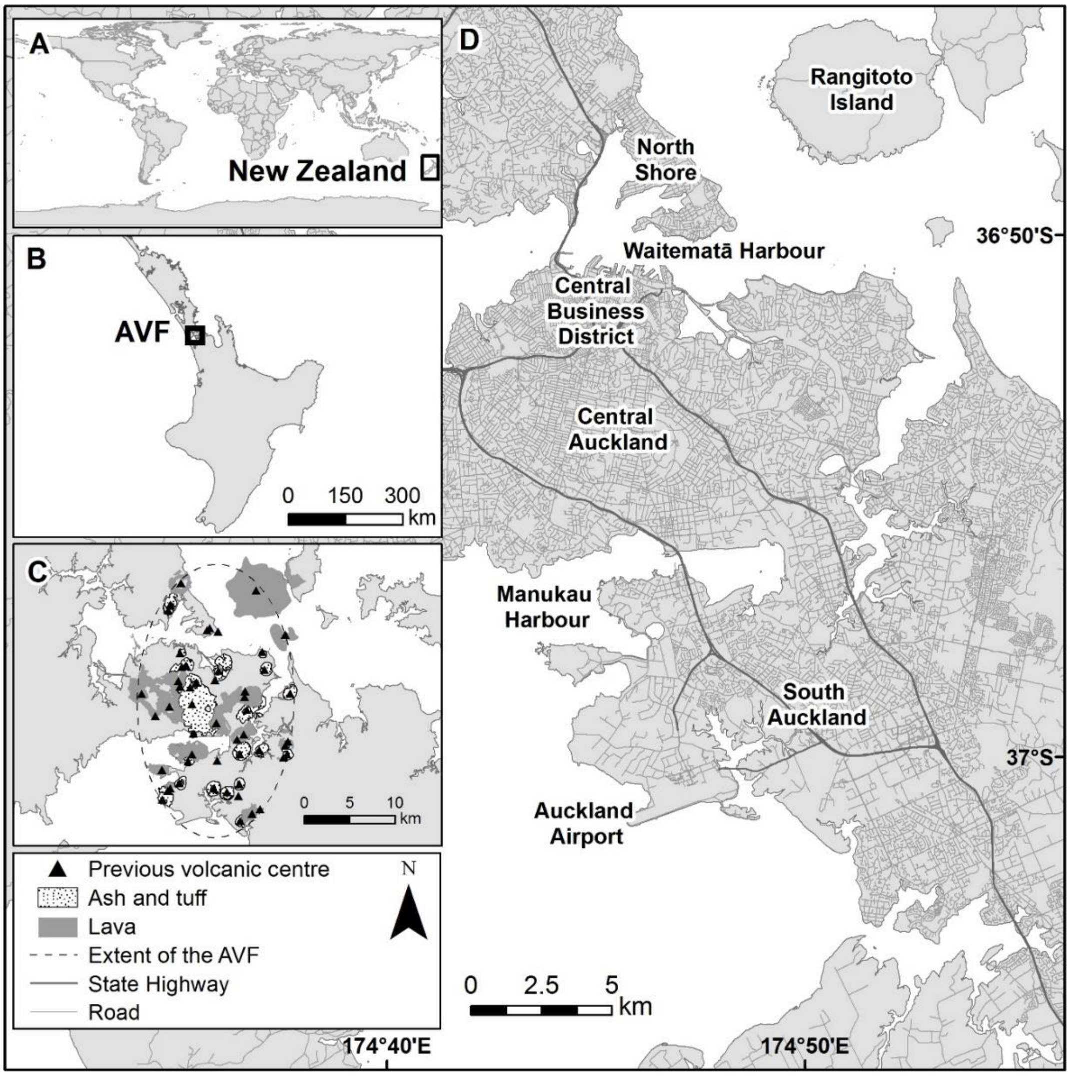

Figure 5.1: A) Location of New Zealand, B) Location of the Auckland and the AVF, C) Distribution of past volcanic centres, eruptive products, and approximate extent of the AVF (Kermode 1992; Hayward et al. 2011; Kereszturi et al. 2014; Runge et al. 2015), D) Geographic locations within Auckland. Roads used as a proxy for population density.

Volcanic risk management in Auckland: a conducive environment for scenario planning

Strong science-practitioner-policy relationships are critical for effective disaster risk governance, which is a key priority area of the Sendai Framework (Paton et al. 1998; UNISDR 2015; Fearnley and Beaven 2018). There has been a strong emphasis from the entire New Zealand civil defence and emergency management environment to facilitate strong linkages between science, practice, and policy and this has been acknowledged as one of New Zealand's strengths in its strategy towards disaster resilience (Ministry of Civil Defence and Emergency Management 2019). In part, this has been achieved through strategically developed research platforms and programmes, such as Determining Volcanic Risk in Auckland (DEVORA), that embed scientists, practitioners, and policy makers within the research and knowledge development process. As a result, these research programmes have fostered close stakeholder engagement and co-production as a key feature of conducting natural hazards and risk research in New Zealand and overall attitudes towards this approach are positive (Beaven et al. 2016; Thompson et al. 2017). This makes the research and disaster risk environment in New Zealand particularly conducive to the collaborative and interdisciplinary requirements of scenario planning.

Given the high degree of risk associated with future AVF volcanism, there is demand from local and national emergency management officials for information products that can inform disaster risk reduction planning (Deligne et al. 2015a, b). Research studies, policy and practice documents and engagement activities have identified a range of information that stakeholders have requested, generally within the following categories: potential direct impacts (e.g., number of damaged buildings or evacuated people, infrastructure loss of service: Blake et a. 2017; Deligne et al. 2017b), potential indirect eruption impacts (e.g., national implications on the flow of imports and exports: McDonald et al. 2017), potential warning time (e.g., evacuation decision-making: Tomsen et al. 2014) and potential post-eruption environment (e.g., clean-up and recovery requirements) (Johnston et al. 1997; Brunsdon and Park 2009; Lindsay et al. 2010; Blake et al. 2017; Deligne et al. 2017a; Hayes et al. 2017, 2018). This information provides useful awareness around the potential scale of disaster and context that decisions will need to be made under.

Scenarios are useful for deriving disaster risk information for AVF disaster risk management planning (Schoemaker 1995; Moats et al. 2008; Brunsdon and Park 2009; Lindsay et al. 2010). In 1997, Johnston et al. (1997) developed a suite of mostly narrative scenarios of expected AVF volcanism. This facilitated exploration of impacts, culminating in a risk assessment for Auckland critical infrastructure (Daly and Johnston 2015). The utilisation of scenarios has been a useful communication tool to envision the potential impacts from a future AVF eruption. In 2008, the transdisciplinary DEVORA research programme was established as a collective effort of Auckland Council (local/regional government body), the Earthquake Commission (national government insurance agency), GNS Science (national geological survey), numerous New Zealand-based universities, and other agencies. It aimed to improve the assessment of volcanic hazard and risk in the Auckland metropolitan area from AVF and distal eruptions, and to provide a strategy and rationale for appropriate risk mitigation (Deligne et al. 2015a). This applied research programme has since promoted integrated multidisciplinary research from geological studies through to volcanic hazards, vulnerability, risk assessments, and development of risk reduction and resilience planning and practices. The close relationship between the science and practitioner communities has led to enhanced understanding of the information requirements of each group. There has been considerable demand from stakeholders for scenarios that can provide insights on issues such as potential infrastructure outages, expected economic losses, and evacuation decision making. Although the 1997 scenarios provided a useful starting point, they do not contain the necessary spatio-temporal hazard footprint and intensity information to inform such studies. Additionally, some aspects of the 1997 scenarios were static across the scenario suite – for example, a common seismic unrest sequence for all scenarios. An understanding of the potential effects of AVF volcanism requires consideration of the range of credible activity. The considerable amount of knowledge gained from the DEVORA research programme means that it is also now possible to obtain enhanced insights into the effects of a future AVF eruption compared to the 1997 scenarios. Therefore, we developed a new suite of scenarios that could meet stakeholder needs and incorporate new knowledge.

Updating the 1997 scenario suite has its beginnings with the development of 'Exercise Rūaumoko' in 2008, which was an all-of-government emergency management exercise designed to test capacity responding to AVF unrest in the lead up to an eruption (Brunsdon and Park 2009; Lindsay et al. 2010). 'Exercise Rūaumoko' was subsequently built upon (through to eruption) for an educational simulation and role-play tool to teach postgraduate students scientific and emergency management concepts (Dohaney et al. 2015; Fitzgerald et al. 2016). This scenario was further developed to explore the impacts of AVF volcanism on Auckland's infrastructure and is known as the 'Māngere Bridge' scenario (Deligne et al. 2015b). The Māngere Bridge scenario has been used to explore impacts on critical infrastructure, mitigation and response requirements, and potential physical and economic losses in the AVF (Blake et al. 2017; Deligne et al. 2017a, b; Hayes et al.

2017; McDonald et al. 2017). These studies have demonstrated to stakeholders the power of such scenarios for contingency planning purposes. However, a noted limitation from these works was the availability and thus use of only one eruption scenario. The geological record indicates that collectively, previous AVF eruptions exhibit a wide range of potential eruption dynamics (e.g., style, hazards, vent location, volume). Therefore, there was a need for a more comprehensive assessment of eruption scenarios that are representative of AVF volcanism.

5.3.2 Developing the DEVORA Scenarios

In this section the context of scenario development for the DEVORA Scenarios and our rationale for the methodological approach we used is presented.

Two basic principles underpinned our scenario development process: 1) using robust scientific evidence, and 2) ensuring streamlined compatibility with current and future applications (e.g., impact assessment). To adhere to these principles, it was necessary to balance relevance, credibility, and legitimacy within the process that we used to develop the scenarios (Cash and Clark 2001; Guston 2001; Cash et al. 2002, 2003; Cash and Buizer 2005; McNie 2007). To do so, we utilised wide stakeholder engagement through workshops, formal review of materials, and information meetings and discussions (Figure 5.2).

Facilitating collaboration within the scenario development framework

The approach we undertook was collaborative in that we sought input from a diverse set of stakeholders. However, the scenario development process was facilitated and managed by a sole party (JLH). We sought regular input through formal consultation and informal meetings from diverse stakeholders throughout the scenario development process to help structure and inform key aspects of the scenarios. Here, stakeholders are defined as anyone involved with the scenario development process including: physical volcanologists, geophysicists, geochemists, disaster risk researchers, and policy advisors, and emergency management officials. To do this we held meetings and workshops with key DEVORA community stakeholders, including volcanologists, disaster risk researchers, policy advisors, geotechnical engineers, infrastructure managers, and emergency managers. During meetings, it became clear that emergency management stakeholders' concerns related strongly to likely societal impacts and potential management requirements rather than the intricacies of the volcanic activity. Practitioner and policy expert's specific interests were diverse but focused much on relevance, including: how long it would take to evacuate different sectors of the city, how to manage re-entry into evacuated areas, and what the post-eruption environment would look like (e.g., damage, economic losses). In contrast, the volcanologists (a stakeholder group) were concerned that scenarios be scientifically credible, accurately reflected the future potential eruptive behaviour of the AVF; they managed uncertainty through use of appropriate analogies, geological information, and expert judgement.

Workshop of draft scenarios

A workshop in November 2016 guided the development of an early draft of the eruption scenarios. Workshop participants were sought through the DEVORA mailing list and was open to anyway interested in participating. This workshop included 23 volcanologists, disaster risk researchers, policy advisors, and emergency management hazard, risk, and resilience advisors. The workshop helped refine scenario requirements to ensure they would meet stakeholder needs and to maintain scientific credibility of the scenarios. Workshop participants were placed into 7 groups that included at least one volcanologist, one risk specialist, and one emergency management official. Each group were given a poster that contained an overview of one of the scenarios, excluding Scenario C - Māngere Bridge as this scenario was already complete by this point (Deligne et al. 2017a). The overview included: maps of the eruptive deposits, an outline timeline of events, eruption characteristics (e.g. eruption duration and volume), and the rationale for why the scenario location was chosen. Participants worked together to answer questions on their assigned scenario to ascertain whether the types of eruptive phenomena that occurred during the scenario was credible and whether the scenario would likely yield useful insights for disaster risk reduction purposes. Next, a discussion involving all workshop participants facilitated by JLH explored ways the scenarios could be improved. The discussion considered likelihood of eruption type and hazards for each scenario, incorporation of uncertainty associated with seismic unrest (e.g., credible detection depth and magnitude), credible worst-case eruption durations for the AVF and potential lulls in activity, increased transparency on selection of eruption parameters, the potential for eruption style transitions and how they would manifest. The final stage of the workshop allowed all participants to add any additional comments to any of the other scenarios using post-it notes. Feedback was compiled and analysed for common themes, and to determine if there were any issues with the credibility or usability for any of the scenarios.

Informal meetings

Throughout the scenario development process there were meetings with stakeholders likely to utilise the scenarios. These included Auckland Emergency Management officials and researchers from disciplines such as transport engineering, land use planning, and economic loss modelling. The purpose of these meetings was to expedite collaboration and to ensure that the scenarios being developed would be useful for a variety of applications. Specific feedback on the scenarios during these meetings was not actively sought, but conversations covered limitations of the science behind the scenarios and the intended timeframes of work. Despite the informal nature of these meetings, they were integral to socialising the scenarios beyond the volcanic hazard community and ensuring wide stakeholder buy-in.

Formal review elicitation

Due to the many components in a credible multi-hazard volcanic eruption scenario, no single individual had expertise spanning the full range of the DEVORA eruption scenarios. Thus, all DEVORA affiliates (past and present) were invited to review the whole report or the parts of the report that fall within their area of expertise. To ensure that reasonable assumptions and appropriate work within the literature were considered in the development of the DEVORA Scenarios, we particularly sought out those that had expertise across the following key areas:

- Monogenetic volcanic processes
- AVF geophysics
- AVF volcanic hazards
- AVF geochemistry

Two rounds of review were undertaken, with the second round involving just those who had participated in the first round. The scenarios were then revised for a final time to reflect feedback received from the detailed review process and published in a scientific report (Hayes et al. 2018).

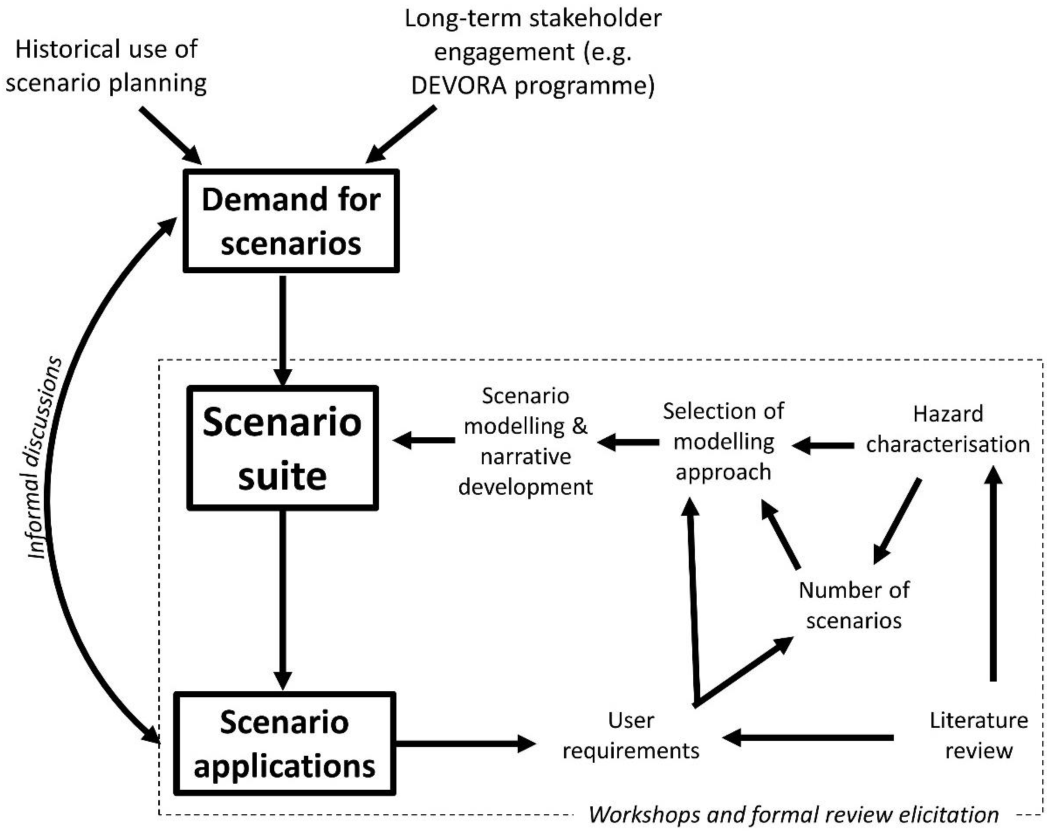

Figure 5.2: The DEVORA scenarios development process.

Identifying user requirements

Volcanic impacts are rarely static in space and time. Volcanic processes can produce a variety of hazardous phenomena at different times before, during, and after an eruption. Responding organisations and communities can undertake measures before, during, or after an eruption that reduce or exacerbate the resulting impacts (Tilling 1989; Horwell and Baxter 2006; Wilson et al. 2012; Pierson et al. 2014; Hayes et al. 2015). For eruption scenarios to be able to produce realistic impacts it is necessary to consider the time and space variations in the hazardous phenomena (Zuccaro and De Gregorio 2013). To do so, eruption scenarios must be time-sequenced with evolving activity as the scenario unfolds, as opposed to a cumulative snapshot of the final distribution of volcanic hazards and feedback from informal discussions with stakeholders was that this was an important dimension that needed to be included within the DEVORA scenarios. Therefore, 'The DEVORA Scenarios' were produced to be time-sequenced as this allows for future analysis of evolving impacts through each scenario.

Due to the importance of spatio-temporal sequencing for use of the scenarios, we decided that the most flexible approach would be to develop a collection of shapefiles of each hazard that occurs through the eruption sequence, as this would allow future researchers to assess the cascading impacts that would occur from the eruption scenarios. To accompany the shapefiles would be qualitative narratives that broadly describe the major events of the eruption scenario. The qualitative narrative was for communication purposes to allow those utilising the scenarios to understand the major events that were occurring in the eruption scenarios.

Determining the number of scenarios

Agreeing upon the number of scenarios to develop is an important part of the scenario development process (Keough and Shanahan 2008). A single scenario is simpler to communicate, but it will come at the expense of legitimacy as it may present a bias indication of volcanism due to not incorporating potential uncertainty, and particularly if some viewpoints are not incorporated into the scenarios (e.g., Girod et al. 2009). However, it is impractical to consider every different combination of events that could occur in the future. A large number of scenarios is also likely to come at the expense of relevance to stakeholders as they will take a substantial amount of time to develop and too much choice can be overwhelming (Girod et al. 2009). Thus, it is necessary to strike a balance between incorporating uncertainty into the scenario suite to serve the needs of end-users and developing too many scenarios.

Our intention was to cover a number of scenarios that would present the most representative variety of potential societal impacts from AVF volcanism, rather than fully categorise all potential dynamics of future AVF eruptions. We considered that focussing on the potential variety of societal impacts would provide scenarios that were relevant and legitimate to stakeholders, whilst still being flexible enough to include the necessary complexity to maintain credibility. The AVF can produce phreatomagmatic, magmatic explosive and magmatic effusive styles of eruption (Allen and Smith 1994), and the eruption style is greatly influenced by local environmental conditions (Kereszturi et al. 2014). Each style produces multiple hazardous phenomena, each with different societal impacts. For example, a fine coating of volcanic ash or lava flowing across the same road necessitates different resources and management requirements. In addition, eruptions within the AVF span several orders of magnitude in erupted volume, which likely effects the duration and intensity of resultant volcanic hazards (Searle 1964; Kermode 1992; Allen and Smith 1994; Kereszturi et al. 2013, 2014). Therefore, to produce a credible representation of AVF volcanism it was necessary to develop a suite of different multi-hazard eruption scenarios in a variety of locations throughout the AVF.

To manage the balance required, we held a brainstorming meeting in 2014 involving volcanology and volcanic impact researchers. At this meeting it was concluded that vent location would likely be a major influence on the type of volcanism and the resulting societal consequences, particularly at locations where strategically important infrastructure nodes were located. Scenario vent location, therefore, was an important consideration when deciding on the number of scenarios. For practical purposes, the probability of the precise location within the AVF for the next vent opening is currently considered to be uniform (Sandri et al. 2012; Le Corvec et al. 2013). Given that there was no evidence to suggest a precise location of the next AVF eruption, geological considerations and locations thought to be of strategic importance for Auckland's urban functionality were used to justify scenario locations. The criteria we used to determine locations for the DEVORA Scenarios were:

- each must fall within the Runge et al. (2015) "tight" elliptical AVF boundary;
- collectively must have a geographical spread across Auckland;
- collectively must allow for the exploration of different eruption styles and hazards that are likely from a future AVF eruption;
- collectively must allow for the exploration of impacts to different exposed assets; and
- each must not be the site of a currently identified volcanic centre.

To facilitate legitimacy in the selection of vent locations, the precise location of each scenario was determined by the group of researchers through discussion and consensus. Through the ensuing discussion we settled on the location of eight scenarios that would cover the requirements listed above (Figure 5.3; Table 5.1).

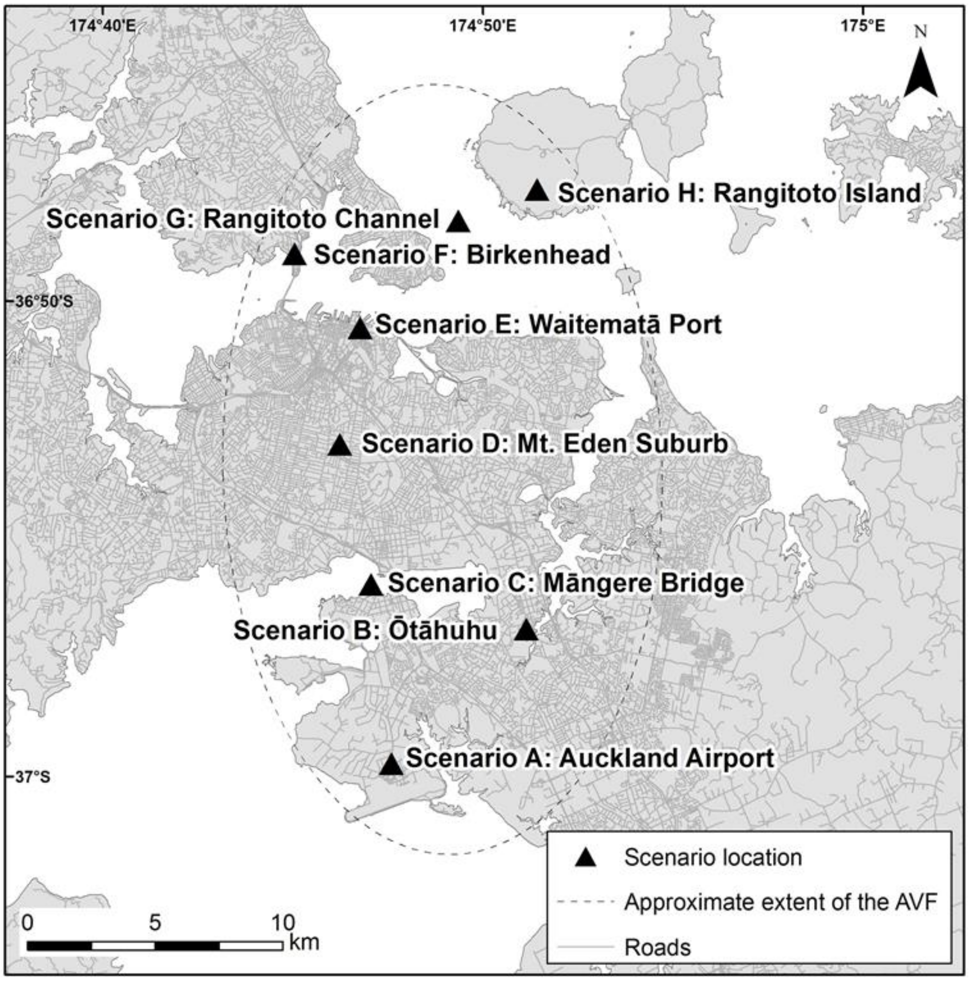

Figure 5.3: The DEVORA Scenario locations and names. Roads included as a proxy for population density. Extent from Runge et al. (2015).

In addition to varying the vent location, we also varied other components in the scenarios that would likely exert a substantial control on the societal impacts:

- Volcanic eruption styles and hazards
- Duration - volcanic unrest activity
- Duration - volcanic eruption sequence
- Volume of erupted deposits
- Hazard modelling parameters

Characterising volcanic hazard

Step 1: Reviewing data availability

There is no historical or instrumental information for developing AVF eruption scenarios as the most recent AVF eruption predates the written historical record and instrumental measurements in New Zealand (Needham et al. 2011) and although Māori would likely have witnessed the eruption, there are no oral traditions that refer to this event (Lowe et al. 2002). Therefore, we were reliant upon geological information and international analogues to develop the DEVORA Scenarios. Information was obtained through literature search. A comprehensive database of articles relating to the AVF was compiled using Scopus, google scholar, and research outputs listed on the DEVORA website. This resulted in a database of 207 journal articles, theses, conference papers/abstracts, and technical reports dating back to 1958. Additionally, throughout the formal review process, additional literature and appropriate analogues was suggested by experts (e.g. geochemists, monogenetic volcanology specialists, and geophysicists). This information was then used as the evidential basis for reviewing the expected range of volcanic activity in the AVF for scenario development.

Table 5.1: DEVORA Scenarios and reasons for selecting them.

Scenario name	Reasoning
A: Auckland Airport	1. Proximity to Auckland Airport (nationally significant infrastructure) 2. Environmental conditions conducive to phreatomagmatic eruptive activity (Kereszturi et al. 2014, 2017).
B: Ōtāhuhu	1. Proximity to an area with a high density of critical infrastructure 2. Environmental conditions conducive to phreatomagmatic activity but could also allow for transition to magmatic eruptive activity (Kereszturi et al. 2014, 2017).
C: Māngere Bridge	1. Exercise Rūaumoko eruption location. This was a highly socialised scenario location because it was used for an all-of-nation civil defence exercise (Lindsay et al. 2010). Criteria given to 'the volcano' in 2008 (Deligne et al. 2015b): • Eruption should start in shallow water to consider range of possible eruption types. • Eruption site should be in an area of mixed socioeconomic groups; • Eruption site could not force closure of State Highway 1 as well as Northwestern Motorway given probable evacuation decisions
D: Mt. Eden Suburb	1. Eruption site likely to result in largest evacuation population. 2. Eruption site located in a residential area. 3. Environmental conditions conducive to magmatic eruption styles (Kereszturi et al. 2014, 2017).
E: Waitematā Port	1. Proximity to Waitematā Port operations. 2. Environmental conditions conducive to phreatomagmatic eruptive activity (Kereszturi et al. 2014, 2017).
F: Birkenhead	1. On the North Shore. 2. Proximity to Auckland Harbour Bridge. 3. Environmental conditions conducive to hybrid eruption style (Kereszturi et al. 2014, 2017).
G: Rangitoto Channel	1. Proximity to shipping channel. 2. Environmental conditions most likely to allow for Surtseyan style eruptive activity (Agustín-Flores et al. 2015b) (Agustín-Flores et al. 2015b).
H: Rangitoto Island	1. Proximity to most recent site of an AVF eruption, potentially important to consider event clustering (Hopkins et al. 2017). 2. Environmental conditions conducive to hybrid eruption style (Kereszturi et al. 2014, 2017).

Step 2: Reviewing the expected range of volcanic activity

In addition to vent location, there are four aspects of volcanism we considered important to characterise to ensure that diverse impacts would manifest in the scenario suite: 1) eruption styles and hazards, 2) precursory activity, 3) eruption duration, and 4) bulk erupted volume. Each of these aspects were reviewed for the AVF and relevant analogous eruptions from around the world. An overview of our analysis and how this information informed the scenario development is presented below.

Eruption styles and hazards

We used geological studies to inform the eruption styles and hazards and analogue eruptions for modelling parameters and unobservable aspects of the scenarios (e.g. unrest activity). The conceptual framework for how volcanic hazards were considered in scenario development is presented in Figure 5.4. We used the following criteria to define the eruption styles and hazards for the DEVORA Scenarios:

- Since >80 % of AVF eruptions have evidence of phreatomagmatic phases, six of the eight DEVORA scenarios include a phreatomagmatic phase.
- One scenario has no phreatomagmatic phase and is located in an area of low phreatomagmatic susceptibility based on Figure 10 of Kereszturi et al. (2014).
- At least one scenario only displays phreatomagmatic activity and is located in an area of relatively high phreatomagmatic susceptibility based on Figure 10 of Kereszturi et al. (2014).
- At least one scenario begins magmatic before transitioning to phreatomagmatic.
- For completeness, there is one Surtseyan eruption style and this is located in an area of similar environmental conditions as the North Head eruption as described by Agustín-Flores et al. (2015b).

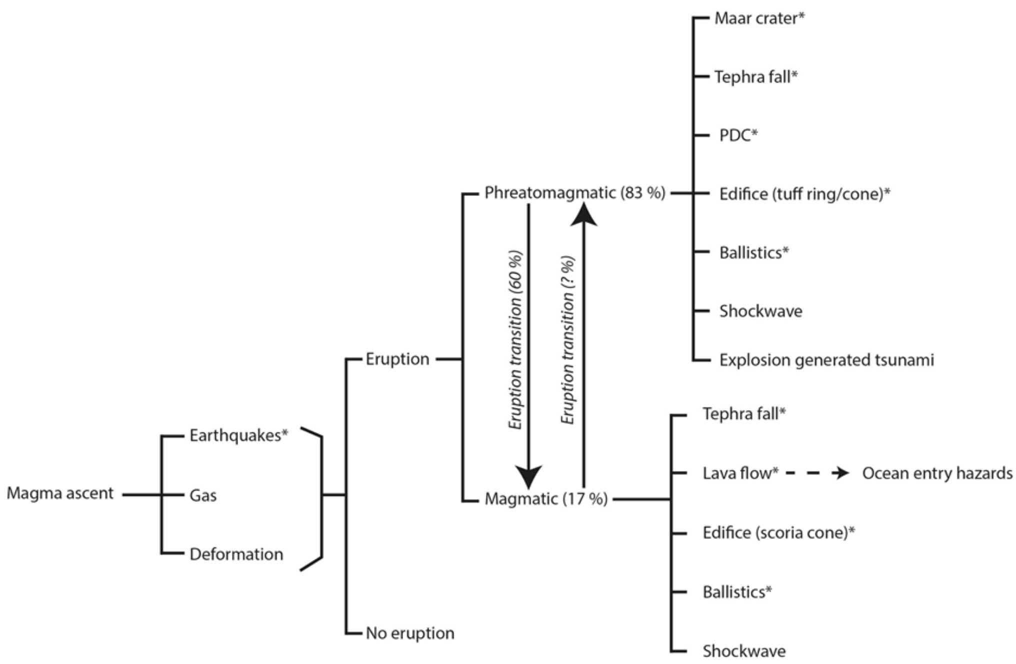

Figure 5.4: Conceptual diagram of AVF eruption hazardscape (Allen and Smith 1994; De Lange and Healy 2001; Magill and Blong 2005; Hayward et al. 2011)(Allen and Smith 1994; De Lange and Healy 2001; Magill and Blong 2005; Hayward et al. 2011). Note: * indicates hazards that have been considered in the DEVORA scenarios

Detection of volcanic unrest

Knowing when a volcano may erupt and characterising volcanic unrest is a key part of volcanic hazard mitigation, as that information can give authorities time to implement contingency plans (Tilling 1989; Newhall and Punongbayan 1996). In areas of distributed volcanism there is an additional component to this as it is also necessary to know where an eruption may occur, which means identifying unrest is even more critical to manage risk. Magma ascent at volcanoes can be detected by changes in three indicator types of precursory activity: seismicity, deformation, and volcanic gas emissions (Sparks et al. 2012). There is very little record of these phenomena within the geologic record and so there is a heavy reliance on the instrumental record or analogues. Thus, identifying the potential characteristics of each and local capacity to monitor each is an important element to consider in scenario development.

Seismology is one of the most useful tools for monitoring volcanoes because of the high incidence of seismic activity associated with volcanic eruptions (McNutt et al. 2015). It has also been suggested that seismic precursory activity currently provides the best basis for detecting magma ascent in the AVF (Sherburn et al. 2007; Lindsay et al. 2010). The GeoNet seismic network in Auckland can automatically detect seismic activity above a magnitude threshold, whilst gas and deformation detection require some human oversight. However, we acknowledge that interpretation of earthquake locations in a volcanological sense also requires considerable human oversight. Thus, for the purposes of these scenarios effort was focussed on developing credible and detectable seismic unrest sequences. The DEVORA scenarios did not feature tectonic swarms unrelated to volcanic processes.

Ascent of magma to the surface in the AVF is likely to be relatively quick (0.01–6 m s-1), suggesting possible ascent durations from source to surface of 4 hours to 116 days (Blake et al. 2006; Sherburn et al. 2007; Brenna et al. 2018). Assuming a constant ascent rate and first detection at 30 ±10 km depth gives potential warning times of 1 hour to 46 days. Ascent rate from the source to the surface is unlikely to be constant, and so the lead time is likely to lie between these values.

To ensure a range of potential unrest sequence durations were considered the following criteria were used to develop unrest sequences:

- Detected earthquakes occur at ≤ 30 ±10 km depth that become shallower over time.
- At least one scenario includes multiple intrusions that fail to reach the surface, resulting in a long-lasting but sporadic period of unrest. The purpose of this is to reflect the limited knowledge around about precursory activity within the AVF.
- Unrest scenarios should fit within the maximum/minimum bounds established in the literature.

Eruption duration

The duration of a volcanic eruption is an important element to consider as it can affect the duration of evacuation/exclusion zones that are in effect. However, the duration of volcanic eruptions can vary considerably (Siebert et al. 2015). As the exploration of temporal components of AVF volcanic eruptions was a key requirement of the scenarios, a range of potential eruption durations for AVF volcanism were considered. It is difficult to predict the duration of eruptions and a global review of all types of volcanism found that the duration can vary from less than one day to centuries (Siebert et al. 2015). To maintain transparency in the scenario development process, we used estimated volumes of previous AVF eruptions and approximate eruption rates to estimate potential eruption durations. Durations of eruptions comparable to those likely in the AVF yields average eruption rates across the entire eruption of 1 - 20 m^3 s-1 (Machado et al. 1962; Thorarinsson et al. 1973; Scandone 1979; Self et al. 1980; Luhr et al. 1993; Blake et al. 2006; Kereszturi et al. 2013; Schipper et al. 2015). We selected average eruption rates within 1 - 20 m^3 s^{-1} that would produce a range of eruption durations spanning from a few days up to approximately one year. The exception to this eruption rate is Scenario C - Māngere Bridge, which included an exceptionally fast outpouring of lava towards the end of the scenario.

Bulk erupted volume

Eruption volumes must be estimated to develop quantitative eruption scenarios as they allow for the quantification of different hazardous eruptive processes (e.g., lava flows and tephra fall). Bulk eruption volume directly represents the volume of material at the Earth's surface, including pore space, meaning that it is a more useful measure of volume for our scenario development than dense rock equivalent (DRE).

Kereszturi et al. (2013)'s comprehensive estimate of minimum volumes of preserved AVF eruption products (excluding medial to distal tephra) was used to constrain the bulk erupted volumes used in the DEVORA scenarios. Kereszturi et al. (2013) reported bulk eruptive volumes of between 3×10^{-4} km^3 (Ash Hill) and 1.1 km^3 (Rangitoto), with a median of 1×10^{-2} km^3. However, eruption dynamics are important to consider, as eruptions with a single phreatomagmatic phase have smaller bulk erupted volumes than those with both phreatomagmatic and magmatic phases (Kereszturi et al. 2014). The omission of medial to distal tephra in the Kereszturi et al. (2013) volume estimates may lead to considerable underestimation of eruptive volumes, as more recent studies indicate it could be a sizable contribution (Hopkins et al. 2017; Slabbert 2017).

To constrain the bulk erupted volumes for the DEVORA Scenarios the following criteria was used:

- Bulk eruptive volume should allow for a variety of eruptive hazards and hazard intensities to be produced across the entire scenario suite.

- One eruption with a bulk erupted volume at the lower end of the range estimated for the AVF.
- Do not include an eruption with >1 km^3 bulk erupted volume because this is likely to be a relatively long-lived eruption (e.g., Rangitoto), which we deliberately exclude from this iteration of the scenarios.

Step 3: Scenario storyboard narratives

One of the criteria for the scenarios was including time-sequenced events throughout each scenario. Storyboard narratives are typically used within the motion picture industry to pre-visualise a sequence of scenes that occur throughout a motion picture (Katz 1991). Storyboard narratives for each scenario were constructed by JLH to describe major events in the scenarios, such as the start and end of major eruptive phases. These narratives helped guide detailed hazard modelling using analytical, empirical, or conceptual models.

Step 4: Spatio-temporal hazard modelling

To appropriately characterise and model volcanic hazards for use in impact and risk assessments it is necessary to have a sound understanding of appropriate hazard intensity metrics that will be used in such assessments. This was done by reviewing published vulnerability/fragility functions and impact models to identify user requirements of the hazard data. Once user requirements were identified, available hazard modelling techniques were considered to identify the most appropriate technique that would provide an adequate level of accuracy and deliver the required outputs for future use. For example, hazards such as tephra fall require detailed attenuation of hazard intensity for use in impact modelling (Wilson et al. 2014; Jenkins et al. 2014). Whilst for other hazards like edifice formation, it can be assumed that anything that is coincident with the hazard will be wholly destroyed, and so the relationship between hazard intensity and impact is considered binary (Wilson et al. 2014; Jenkins et al. 2014). This led us to characterise each AVF hazards into three categories:

1. Hazard intensity spatial variation is an important variable in determining impact

2. Hazards that will potentially exhibit mostly a binary relationship between hazard and impact (i.e. hazard exposure = complete destruction).
3. Hazards that we acknowledge have the potential to occur during a future AVF eruption, but there is a lack of resources to accurately model and/or there is very little information of how impacts relate to the hazard.

For hazards that fall within category 1 (Table 5.2), available impact models and fragility functions were reviewed to determine the most appropriate hazard intensity metrics to use (Jenkins et al. 2014; Wilson et al. 2014). The required hazard intensity metrics were then an important consideration when deciding on the analytical or empirical model(s) that would be used to model the hazard. For category 2 hazards, the spatial extent would be a sufficient measure of hazard for our purposes, meaning that we focussed on characterising only the footprint of these hazards. For category 3 hazards, it was not possible to model the hazard. In these instances, qualitative descriptions were made, but we endeavoured to keep descriptions broad such that if capacity to model the hazard becomes available in the future, they can seamlessly be added into the DEVORA Scenarios.

As it was our objective to produce multi-hazard scenarios, it was necessary to consider the effects each hazard might have on other hazardous processes. However, existing 'out of the box' hazard models often only represent a single eruption hazard (e.g., just tephra fall). Thus, it can be difficult to integrate a variety of volcanic hazard models to ensure the collective outputs make logical sense. Thus, throughout the modelling process the implications that each model output would have on other elements of the scenario had to be considered. For example, our approach to lava flow modelling relied upon topography, which could potentially change during an eruption through the construction of an edifice and/or development of a maar crater. To overcome this, time sequenced maps were constructed that displayed the eruptive products and features of the eruption scenario to inform where lava would possibly flow. Consequently, lava flow modelling had to be undertaken following modelling of all other processes.

Table 5.2: Expected AVF hazards, the approach taken to characterise the hazards, and the scenarios each hazard appears in

Expected AVF hazards	Hazard characterisation used in DEVORA Scenarios	Approach used to model	Information used for modelling	Scenarios hazard appears in
Tephra fall	Category 1: Deposit loading (kN m^{-2}) and thickness (mm).	Tephra2 (Bonadonna et al. 2014).	Eruption parameters and climatological information.	A, B, C, D, E, F, G, H.
PDC	Category 1: Deposit thickness (mm) and PDC dynamic pressure (kPa).	Energy cone (Palma 2013) and empirical relationships based on Brand et al. (2014).	Eruption parameters, Digital Elevation Model (DEM).	A, B, C, E, F, G, H.
Ballistics	Category 1: Impact energy (Joules).	Ballista (Tsunematsu et al. 2014).	Eruption parameters.	A, B, D, E, F, G, H.
Tuff ring	Category 2: Binary impact.	Empirical relationships.	Systematic collection of tuff ring morphometry in study area.	A, B, C, E, F, H.
Maar crater	Category 2: Binary impact.	Empirical relationships.	Systematic collection of maar crater morphometry in study area.	A, B, C, E, F, H.
Volcanic cone (scoria, tuff)	Category 2: Binary impact.	Empirical relationships.	Systematic collection of cone morphometry in study area.	B, C, D, F, G, H.
Lava flow	Category 2: Binary impact.	Expert judgement.	Systematic collection of lava volume, DEM.	B, C, D, F, G.
Volcanic gas emission	Category 3: Not modelled - expect future development.	Not modelled - expected future development.	N/A.	Qualitative description only in scenarios.

Expected AVF hazards	Hazard characterisation used in DEVORA Scenarios	Approach used to model	Information used for modelling	Scenarios hazard appears in
Lava ocean entry hazards (e.g., vaze, littoral explosions, lava front collapse causing large waves)	Category 3: Not modelled - potential future development.	Not modelled - potential future development.	N/A.	Qualitative description only H. Small tsunami described in C.
Shockwave	Category 3: Not modelled - potential future development.	Not modelled - potential future development.	N/A.	Does not feature in any scenario.
Explosion initiated tsunami	Category 3: Not modelled - potential future development.	Not modelled - potential future development.	N/A.	Not included in the scenario suite.
Earthquakes	Category 1: Magnitude, depth, and horizontal location	Expert judgement.	Likely earthquake magnitudes, ascent rates, and detection depth.	A, B, C, D, E, F, G, H.

One particularly unique feature of the AVF is the existence of a major urban development built upon it. This yields the question of whether the built environment could influence how hazards and their intensity vary spatially (e.g., PDC). Some authors have highlighted this possibility for PDC (Gurioli et al. 2007; Zanella et al. 2007; Doronzo and Dellino 2011, 2014; Jenkins et al. 2013). However, as yet, there is no known tool calibrated for the AVF, and very little practical advice available on how such modelling could be conducted. Therefore, we chose to ignore such effects, acknowledging it as a limitation to the approach taken.

Step 5: Development of detailed scenario narratives

Scenario narratives in many disciplines are useful for analysing impact, vulnerability, and risk, and communicating complex processes that are representative of potential hazardous events (Ghanadan and Koomey 2005; Hallegatte 2009; Rounsevell and Metzger 2010; Kriegler et al. 2012; Birkmann et al. 2015). From this perspective, the scenario narratives were written to be representative of the eruption scenario. The intention here was not for high precision and detailed rationale for each event that happens in a given scenario, but rather a written qualitative description of relevant physical processes that were occurring. Scenario narratives were presented in conjunction with cumulative eruptive product maps that provided a visual aid to where different eruptive products were spatially located at specific moments throughout the scenario timeline. Cumulative eruptive product maps were produced by spatial modelling of different volcanic processes.

5.3.3 The DEVORA Scenario Suite

The DEVORA scenarios have been comprehensively outlined in a technical report (Hayes et al. 2018), which included rationale, modelling, assumptions, scenario narratives at a daily to monthly breakdown, and eruptive products maps for each scenario. Scenario C - Māngere Bridge was developed at an early stage to the other seven scenarios and is discussed elsewhere (Deligne et al. 2015b, 2017a; Fitzgerald et al. 2016). The DEVORA Scenarios have associated shapefiles for each hazardous process that was modelled and are time-sequenced.

A key aim of the scenario development process was to capture a range of credible scenarios that could occur during a future AVF eruption. Areas of particular importance to ensure a range of values were: duration of unrest, duration of eruption, eruption volume and proportional breakdown of volume into different eruptive products, and spatial distribution of eruption hazard. For illustrative purposes, an overview of the eruptive products produced during each scenario is presented in Figure 5.5 (proximal eruptive products) and Figure 5.6 (extent of tephra distribution in Auckland). The DEVORA Scenarios also involved a variety of different eruptive styles and occur over different periods of the year (Figure 5.7).

The detected unrest durations for the DEVORA eruption scenarios falls within 4–660 days (Figure 5.7). All unrest durations fit within the estimated range for detected magma ascent estimated for in the AVF, except for Scenario H (Rangitoto Island), which was developed to include multiple intrusions and thus a long, but sporadic, lead-in time. Eruption durations used in the DEVORA scenario suite are 4-320 days (Figure 5.8), excluding the time it required for lava to cool down, a potentially important consideration for physical land recovery. The range of bulk erupted volumes across the DEVORA scenario suite is 1.2×10^{-2} (Scenario E — Waitematā Port) to 1.9×10^{-1} km^3 (Scenario H — Rangitoto Island) (Figure 5.8A). Different eruption products also have different bulk erupted volumes, indicative of the influence of different eruptive products through the scenario suite (Figure 5.8B).

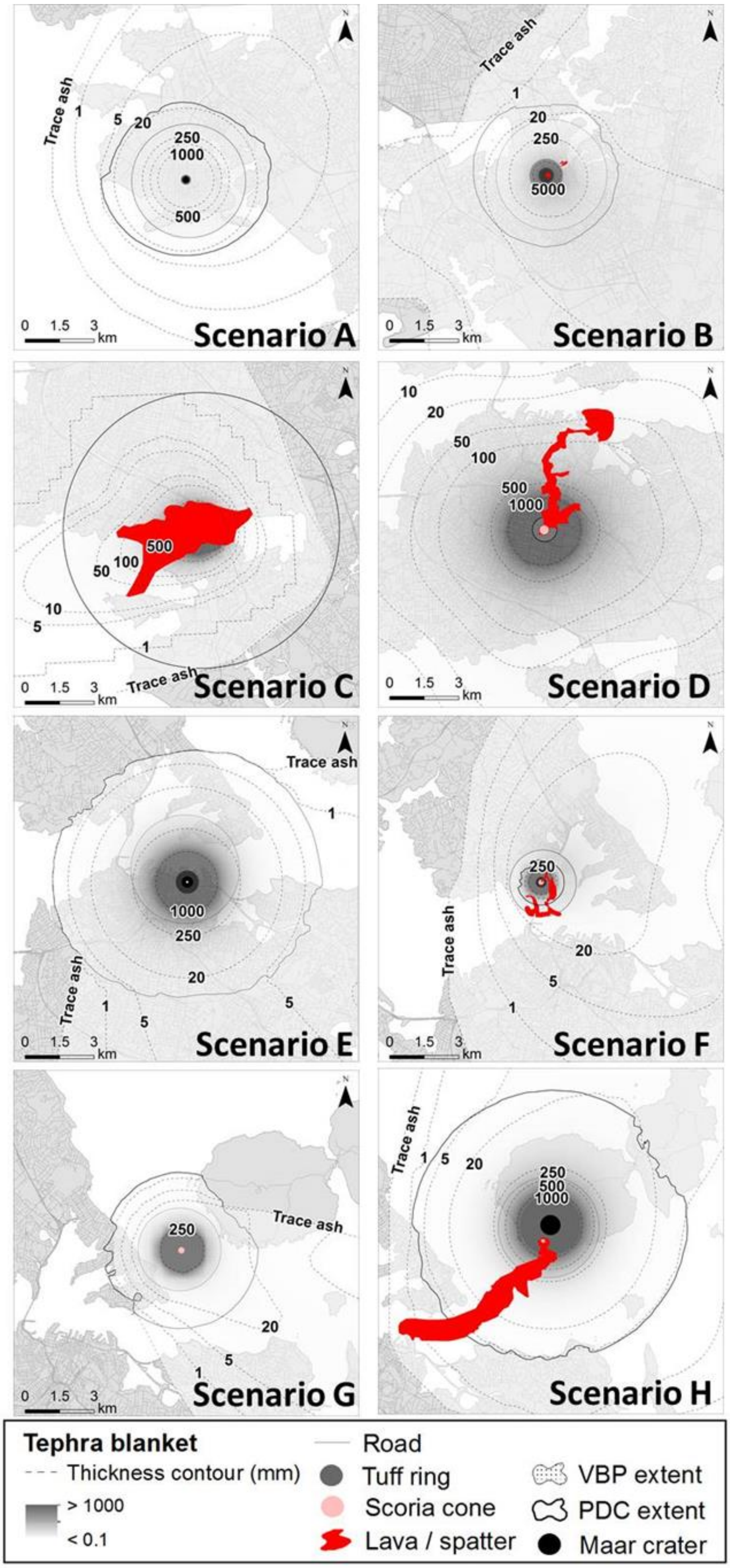

Figure 5.5: Proximal deposits of each scenario. Note: Scenario C based on different modelling parameters from the rest of the scenarios (Deligne et al. 2015b, 2017a).

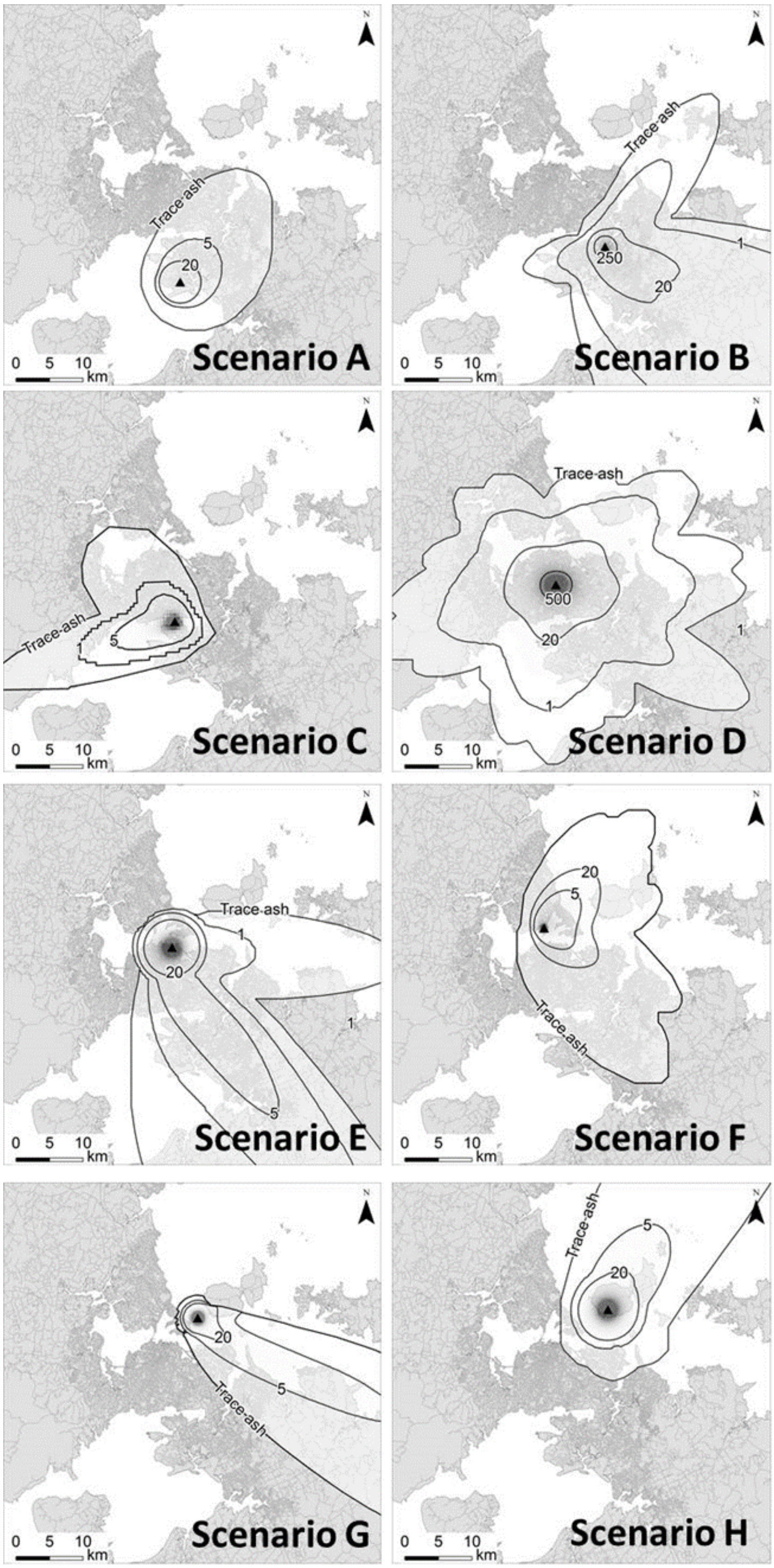

Figure 5.6: Extent of distal tephra fall of each scenario. Black line indicates extent of trace ash, black triangle indicates location of vent.

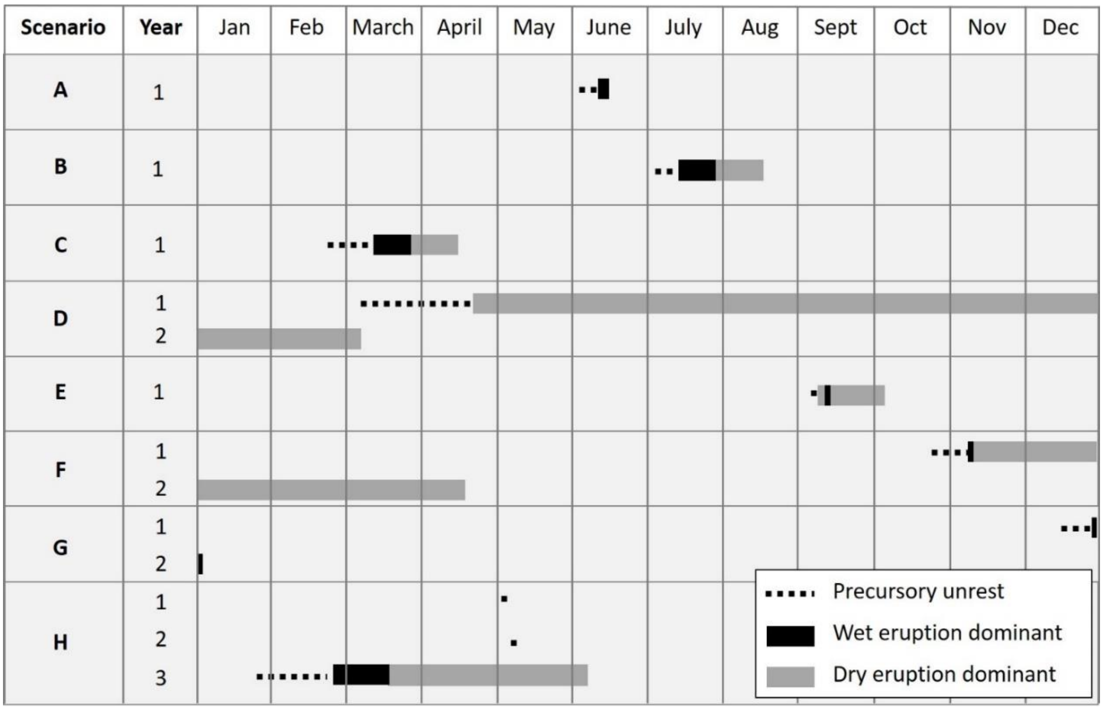

Figure 5.7: Timelines of each of the DEVORA scenarios. Year is used to indicate the year of volcanic activity for scenarios that span more than one calendar year.

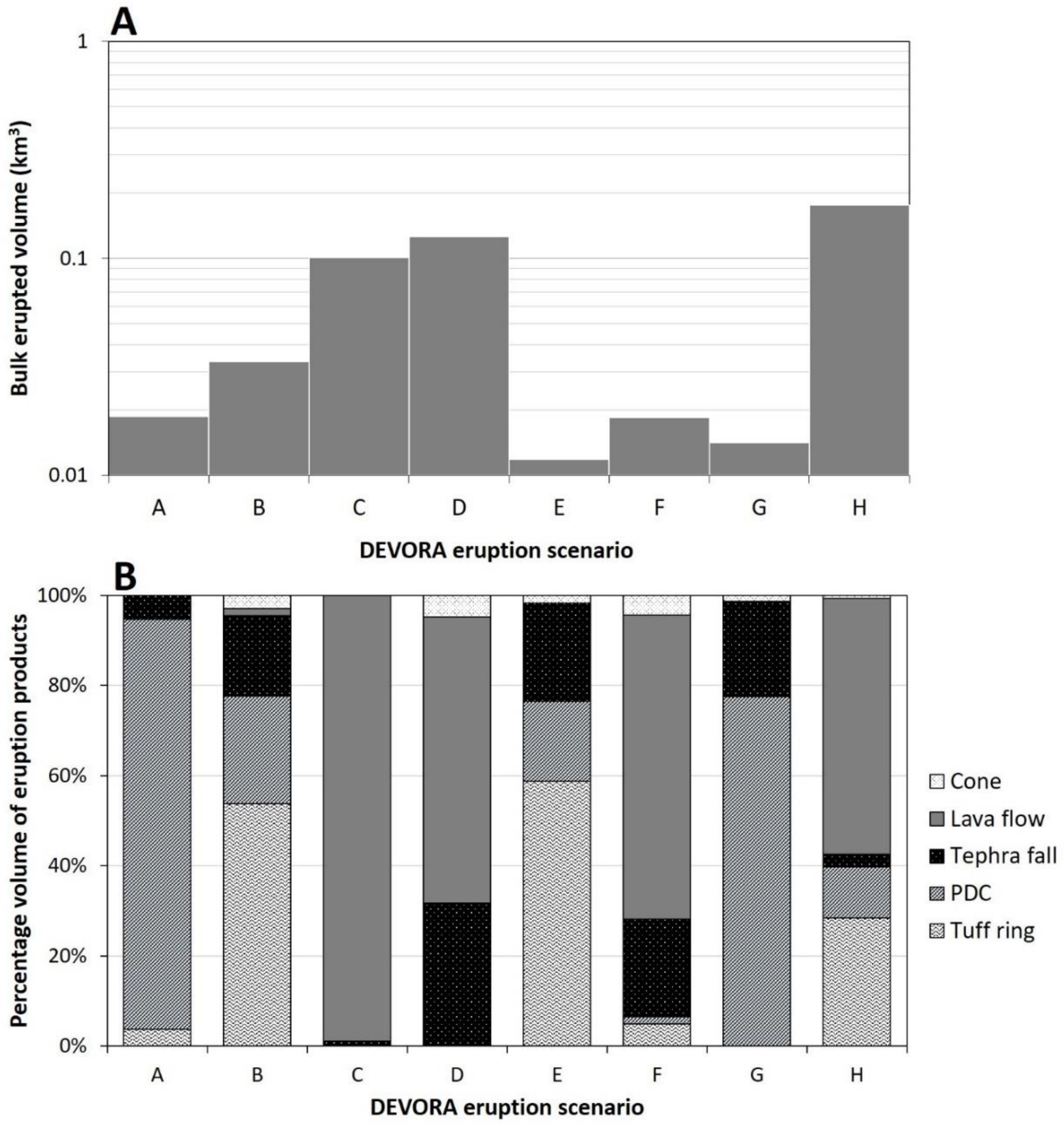

Figure 5.8: A) Bulk erupted volume and B) relative proportion of different eruptive products of each of the DEVORA scenarios

5.4 DISCUSSION

5.4.1 Benefits of the scenario development process

This work makes several contributions to volcanic hazard and eruption scenario development.

Firstly, it outlines an approach for developing a suite of scenarios in widely distributed volcanic areas: a useful middle ground between fully probabilistic and fully deterministic approaches. Secondly, it provides a framework for integrating diverse information and the expertise of a wide range of stakeholders. Volcanologists, disaster risk researchers, policy advisors, and emergency managers all played a critical part in the development of the DEVORA Scenarios. Volcanologists ensured that the scenarios were scientifically credible, whilst disaster risk researchers, policy advisors and emergency managers ensured the scenarios remained relevant. Incorporating all views and balancing stakeholder needs ensured that the scenarios established relevance. Thus, the DEVORA scenarios can be used in the future as a reliable collaborative tool for future disaster risk research for the AVF.

Thirdly, the scenario development process allowed for the identification of several major research gaps relating to AVF volcanism. For example, lava flow and PDC hazards represent major sources of potential damage and loss from a future AVF eruption, but our ability to model these is quite limited for the AVF. Gas dispersion is an acknowledged hazard but has yet to be modelled for the AVF and so only a cursory understanding of the effects it may pose during a future AVF eruption is available.

5.4.2 Challenges and limitations

Overcoming challenges

Eliciting input from diverse stakeholders can be challenging. Establishing 'buy-in' to the process was the first challenge to be overcome. This is important to ensure that stakeholders have confidence in the work and that their time and expertise will be appropriately utilised. This was facilitated by leveraging existing and long-term relationships built through regular engagement. Regular events (e.g., annual forums and workshops) and collaboration with researchers in other research programmes was a beneficial element to ensuring engagement amongst stakeholders. A second useful factor was leveraging and adapting an already well socialised piece of work. In our situation, we built upon an existing national disaster simulation scenario 'Exercise Rūaumoko', which many stakeholders were familiar with and could see the potential benefits of additional scenarios for disaster risk reduction purposes. The development of the Māngere Bridge scenario provided insights to the utility of such scenarios and drove demand for an entire suite of scenarios.

It can be challenging to manage input from a diverse range of stakeholders with different backgrounds and expectations. The challenges involved with bringing together this group of stakeholders to work towards a common goal of robust and usable multi-hazard eruption scenarios for the AVF included: terminology/jargon/language, and time constraints. Each of these challenges are discussed below.

Terminology is a commonly cited challenge associated with conducting interdisciplinary research and it can be easy to become distracted debating terminology, which presents a risk to the project outcomes (Golde and Gallagher 1999; Jakobsen et al. 2004; Davidson 2015; Thompson et al. 2017; Hardy 2018). An example from our experience is that “geophysical” had different meanings to different disciplines and individuals. We opted to utilise a shared meanings approach (Hardy 2018). The shared meanings approach advocates for acceptance of different disciplinary approaches to vocabulary. In a practical sense, this required co-writing of the written report on the scenarios, where stakeholders could have input into the writing and state areas that were confusing or highlight terminology that they did not understand. We also developed a glossary of technical terms to provide clarity regarding how we were using each term.

An important consideration is that the scenario development process can represent an ‘end’ of the knowledge development process for some stakeholders (e.g., physical scientists) and the ‘beginning’ for others (e.g., impact researchers, emergency managers). Incorrect interpretations, misunderstandings, and intellectual property issues are abundant when conducting interdisciplinary research (Golde and Gallagher 1999; Davidson 2015; Hardy 2018). Thus, a delicate balancing act was required that promoted the timely completion of the DEVORA Scenarios for user uptake (ensuring relevance) and paying due respect to the substantial knowledge development that had been conducted by previous researchers (ensuring credibility and legitimacy). By opening the scenario review process to all DEVORA affiliated researchers (past and present), we gave scientific researchers the opportunity to showcase to how their research was being utilised, and to confirm suitable application (ensuring legitimacy). This helped clarify misunderstandings and incorrect interpretations and enhanced the legitimacy of the scenarios amongst stakeholders.

As the DEVORA Scenarios were to be utilised in planned research projects outside of DEVORA we were constrained in the time to develop the scenarios. This meant that we often had to find practical solutions to complex scientific problems that arose. This was a challenge at times because scientific stakeholders advocated for substantial research questions to be answered beyond the scope of the work. For example, modelling of PDC hazard was a major challenge because no models currently exist that could integrate the type of PDCs expected in the AVF and the urban environment that they will likely travel across during a future AVF eruption. To produce a model capable of this would have required considerable time and financial investment beyond the scope of the work and delayed the production of the DEVORA scenarios substantially. Therefore, to manage these issues required careful consideration of the matters raised, transparent communication, and clear reporting in the final document about the limitations.

Limitations in the scenario development process

During the development of these scenarios it became clear that further work is required in some areas, which has meant we have had to undertake a bespoke approach to modelling AVF volcanic processes. Great strides have been made understanding the complexities of AVF volcanism, but further benefits could be gained by translating this information into guidance for useful hazard and risk applications. This is particularly important if each volcanic hazard is to be integrated in the future within a systemic probabilistic multi-volcanic hazard framework that considers cascading and compounding hazardous processes, like those expected to affect Auckland during a future AVF eruption.

For some hazards such as tephra fall, there are a variety of models available to choose from that provide reasonable outputs at relatively low computational cost (e.g., ASHFALL, Tephra2). For lava flow, we were unable to identify a single model that would be able to produce outputs that would fulfil our information requirements and were calibrated for use in the Auckland context (Tsang et al. in prep). Since development of an Auckland specific model was beyond the scope of our work, expert judgement was used to manually model the lava flow through the scenarios with effusive activity. A further limitation is that hazard models in volcanology typically only consider a single specific hazardous process (e.g., tephra fall, lava flow), with little in the way of linkages across a range of different physical processes. However, volcanoes erupt as events that include multiple interacting hazardous processes. Therefore, it was necessary to consider how model outputs from each hazard may interact and influence another hazard. For example, it was important to consider topographical changes that occurred (e.g., development of a maar crater or scoria cone) that might influence where lava would likely flow. To consider the multi-hazard interactions we were reliant on expert judgement.

We acknowledge it is plausible that eruptions could last for longer than 12 months in the AVF but have avoided these potential prolonged scenarios. This is because such eruptions could substantially alter local environmental conditions, which would require highly speculative assumptions such as changes to hydrology. A long-lived eruption scenario may be developed in the future and added to the suite of scenarios.

Although taking an interdisciplinary approach had many benefits to the scenario development process, it is acknowledged that the challenges associated with undertaking interdisciplinary research may limit the ability for others to translate this approach to other environments, particularly where specialists are lacking and/or relationships between stakeholders are not well developed.

5.4.3 Applying this in other volcanic settings

The DEVORA Scenarios were produced in a setting that has a relatively high degree of geological information to draw from, but no historical or instrumental records. This meant we also had to rely heavily on analogue eruptions. How might the approach change if we had access to historical information? If we had written records or indigenous knowledge of a past eruption, we would very likely have looked to develop this as a scenario. Although it is extremely unlikely a future eruption would repeat the events of a previous eruption, using a highly socialised eruption scenario would serve as a useful communication device to explain expected phenomena. After all, the utility of a scenario is to envision, anticipate, communicate, and train for potential issues that may arise in a disaster and not a rigid prediction (Alexander 2015). Utilising oral tradition and indigenous knowledge would also serve as a valuable co-design and engagement process that would allow two-way knowledge transfer (King et al. 2007; Becker et al. 2008; Cronin and Cashman 2008; Mercer et al. 2012; Hiwasaki et al. 2014).

There are volcanoes around the world that have longstanding instrumental measurement records (e.g., Stromboli, Etna, Kīlauea). If we had access to instrumental measurements (e.g., seismicity, gas, and deformation) obtained from previous AVF eruptions we would have likely used these to further develop our unrest scenarios, including during and following the eruptive phases. However, it would be important to acknowledge that the instrumental record would likely still be limited in observations (i.e. at maximum several decades with varying data quality) and so care would need to be taken so that recency bias does not manifest to ensure that credible scenarios not captured by the instrumental record are still considered.

One of the major sources of uncertainty in this work was the vent opening location. However, in many volcanic settings the vent opening location is known to a high level of precision and certainty. How might our approach have changed if we had some certainty about where the next AVF eruption would occur? We would have focussed our efforts on constraining credible eruption scenarios for that specific location and may have changed the number of scenarios we chose to produce. However, our focus on exploring potential impacts would remain as this is a core aspect of ensuring the scenarios were relevant for stakeholders.

5.4.4 Implications for future research

Our expectation is for the scenarios to be used as a collaborative tool within AVF volcanic impact and risk studies and to support volcanic risk mitigation and asset management practices. Work is currently underway exploring the consequences of the full suite of scenarios to Auckland, which will provide a more complete understanding of impacts expected from a future AVF eruption. The DEVORA Scenarios represent a step towards testing the sensitivity of location and eruption dynamics of syn- and post-eruption impacts in Auckland. To achieve this, DEVORA is using a staged approach to move towards a probabilistic assessment of risk in Auckland (Figure 5.9). This process began with the development of the Māngere Bridge scenario, and now in this paper seven additional eruption scenarios have been developed. The next step will be to develop scenario ensembles, which will simulate the scenarios across an Auckland grid and assign a conditional and relative probability to each scenario (supplementary material 1). This will allow for exploratory modelling and investigation of elements of robust policy decisions. The vision is to have a ready to use rapid impact assessment tool with a pre-run library of impact scenarios that could be utilised during a future eruption crisis as well as to explore long-term pre-event policy decisions (e.g., how long-term changes in land use will influence expected losses).

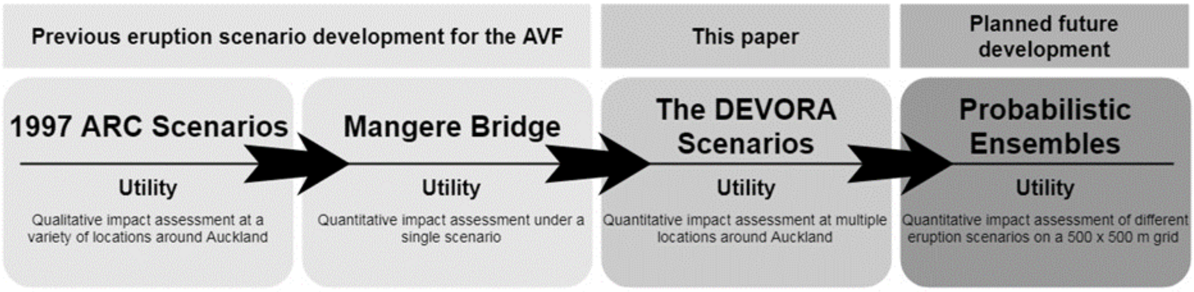

Figure 5.9: Past, present, and future DEVORA AVF scenario development.

Knowledge development towards a generic scenario builder model would be useful for developing fully probabilistic scenarios in the AVF. Several areas of development are required for this to occur. Better understanding of appropriate hazard models, including validation or development of models specific to the AVF (including interactions between the built environment and the physical phenomena) and probabilistic understanding of the required input parameters is necessary. Particular utility would come from models of PDC, lava flow, tephra fall, and ballistics.

Locations like Auckland, where society is exposed to many different and overlapping volcanic hazards, suggests it is important to development knowledge around multi-hazards of volcanic eruptions. In particular, advice and knowledge that contributes towards conducting integrated multi-hazard modelling in volcanology is necessary. Additionally, spatio-temporal and dynamic hazard models for most volcanic hazards are still in their infancy. Further development of such modelling approaches would greatly enhance scientist's ability to communicate how hazards can evolve through eruption sequences.

5.5 CONCLUSIONS

In this contribution we have provided a template for how to produce a volcanic eruption scenario suite. We have presented an overview of our interdisciplinary approach to developing eight new eruption scenarios for the AVF. The DEVORA Scenarios cover a credible range of erupted volumes, durations, detected unrest durations, hazards, and potential volcanic centre locations. We anticipate they will serve as the basis for future studies assessing a range of impacts to Auckland's urban functionality and will facilitate discussions about the potential disaster risk reduction requirements in the event of a reactivation of eruptive activity within the AVF. Our approach required utilising a variety of scientific disciplines to underpin evidence used throughout the scenario development process. The DEVORA Scenario development process was driven by a strong interest from stakeholders on the potential variety of impacts from future volcanism in the AVF, and this served as a complementary aspect of the scenario development process along with underpinning scientific evidence. The interdisciplinary approach was a considerable success at ensuring the scenarios were scientifically credible, relevant to all stakeholders, and legitimised within the DEVORA research community of practice. The end product was a suite of eruption scenarios that will serve the community for years to come, but equally important as the final product was undertaking the process and learning the needs and limitations of all stakeholders. Although the approach undertaken in this work involved development of an interdisciplinary framework for producing a suite of eruption scenarios in areas where future volcanism is widely distributed and highly uncertain (e.g., volcanic fields and calderas), much of the interdisciplinary approach is transferrable to any volcanic setting.

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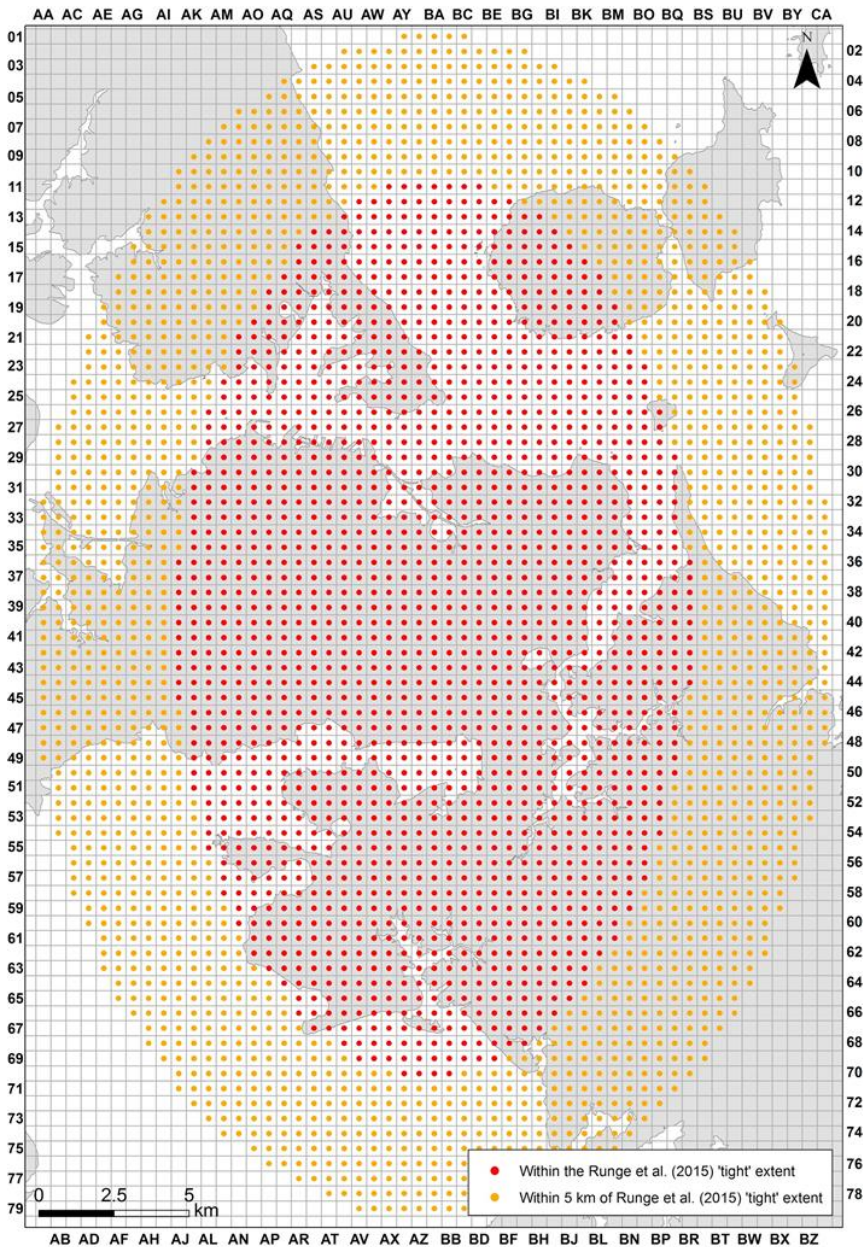
5.7 SUPPLEMENTARY MATERIAL 1



S1: DEVORA grid nodes for probabilistic scenario ensembles. Note: 5 km beyond the Runge et al. (2015) extent is to indicate a qualitatively less likely area of future vent emergence that cannot be ruled out.

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Chapter 6: Modelling Disaster Waste Generation from Volcanic Events

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ABSTRACT

Disasters can cause substantial quantities of disaster waste that must be managed for effective response and recovery. Modelling the potential quantities and types of waste expected after disasters has been widely applied for a variety of hazards (e.g., earthquake, hurricane, flood, tsunami). However, there has been limited consideration of modelling disaster waste as a result of volcanic eruptions, which can generate considerable disaster waste volumes and management issues. In this work we develop a modelling framework for assessing disaster waste types and quantities after volcanic eruptions affecting urban environments. The framework facilitates quantification of different waste types resulting from damaged buildings and classification of different clean-up zones. The framework is based on vulnerability models and heuristic analysis of the likely waste generated at different states of damage from tephra fall, pyroclastic density currents, and lava flows. Clean-up zone classifications are developed by identifying key management requirements for different urban land use types. The waste streams are likely to be highly mixed and require substantial waste sorting processes for appropriate disposal. Clean-up zonation helps identify the scale of area that is likely to be subject to challenging waste management conditions such as health and safety risks associated with the eruption and the waste, and the likely personnel and equipment required to clean each area. We apply the framework to a suite of volcanic eruption scenarios from the Auckland Volcanic Field (AVF), New Zealand. Our modelling outputs indicate that there could be as much as 11-14x10^6 tonnes of building debris generated from future AVF eruptions, but most scenarios generated 2-3x10^6 tonnes of building debris. In addition to building debris, substantial quantities of tephra will require removal (1.5 – 12x10^9 tonnes). These quantities are likely to put intense stress and potentially exceed existing waste processing and handling facilities in Auckland. This framework provides a rapid assessment approach for identifying disaster waste management requirements pre-disaster (e.g., using hypothetical scenarios) or post disaster (e.g., using preliminary hazard and damage information) for recovery planning.

6.1 INTRODUCTION

Disasters can produce large quantities of waste products that can be challenging to manage during response and recovery (Reinhart and McCreanor, 1999). Characterising and quantifying the waste likely to be generated from a potential future disaster is considered best-practice for disaster contingency planning (Federal Emergency Management Authority 2007; United States Environmental Protection Agency 2008; UNOCHA 2011; Brown 2014). Assessing disaster waste generation informs identification of waste disposal sites, necessary resources (e.g., number of dump trucks, diggers), and potential environmental and public health risk management requirements (Brown 2014; Hayes et al. 2017). Both empirically and heuristically derived approaches have been developed to assess and characterise waste after earthquakes, hurricanes, and floods (Chen et al. 2007; FEMA 2013a, b, c; Yamanaka et al. 2013; Brown 2014; García-Torres et al. 2017). Empirical approaches have been based on statistical analysis of previous events comparing hazard intensity (e.g., flood height) with waste quantity (Chen et al. 2007; Hirayama et al. 2010 a, b; FEMA 2013b). These approaches are useful for hazards that occur commonly enough that statistically significant relationships can be derived. Due to variability in international building practices and community risk tolerance these approaches often cannot be easily transferred to other localities. Rapid and automatic assessment of debris post-disaster using Earth observation techniques has also been investigated (Labiak et al. 2011; Koyama et al. 2016; Cappucci et al. 2017; Yoo et al. 2017). Although useful during a post-disaster response, these approaches cannot be directly used for pre-event planning purposes. Damage modelling to heuristically quantify and classify the likely debris that would be generated through material stock analysis (quantifying material types such as concrete, wood, metal in a defined system) has been used in a few contexts with credible results (Tanikawa et al. 2014; García-Torres et al. 2017; Tabata et al. 2018). This approach often assumes the damage ratio is equal to the proportion of the building that would become waste following a disaster (Lemieux et al. 2010; Tanikawa et al. 2014; García-Torres et al. 2017). This approach is useful for both pre-event planning (e.g., using hypothetical hazard scenarios) and post-event rapid impact assessments (e.g., using preliminary damage data), but is reliant on having sufficiently accurate and complete building inventories and associated vulnerability information of the exposed community.

Despite the abundance of applications for earthquakes, hurricanes, floods, and tsunami, approaches for volcanic eruptions are less advanced and for many volcanic hazards are non-existent. Approaches have been developed and applied to quantify tephra volumes that must be managed or cleaned up following volcanic eruptions, however this is just one of many volcanic hazards that can occur during eruptions (Hayes et al. 2017, 2019; Johnston et al. 1997; Magill et al. 2006; Biass et al. 2017). Although tephra is the most widespread clean-up issue after volcanic eruptions, areas close to the vent can be subjected to a variety of highly damaging volcanic hazards such as pyroclastic density currents (PDCs), ballistic projectiles, lava flows, and lahars. The specific hazards that manifest and the spatial distribution of their hazard intensity will vary depending on the volcano and the eruption size and style (Tilling 1989; Connor et al. 2001). Volcanic hazards have previously caused substantial building damage through a variety of different mechanisms such as dynamic pressure, static load, heat, and chemical alteration (See Table 2.1). Therefore, a more comprehensive multi-hazard approach to assessing disaster waste clean-up for volcanic eruptions is necessary.

To assess the disaster waste generation from volcanic events requires converting damage estimates obtained through risk/impact assessments into quantities and types of waste requiring management. However, there is currently no framework that outlines how such a process could be conducted for volcanic eruptions. The aim of this paper is to develop a framework for quantifying the building waste generated from volcanic eruptions to facilitate a more complete understanding of the disaster response and recovery management requirements. We begin by using established building vulnerability model frameworks for different volcanic hazards to identify the likely waste generated at different damage state levels. We then demonstrate the applicability of our approach using a scenario approach for the Auckland Volcanic Field, New Zealand. Finally, we discuss the implications for disaster waste management in Auckland following AVF eruptions, and the benefits, challenges, and limitations with the approach we have developed.

6.2 METHOD: DEVELOPING A VOLCANIC ERUPTION DISASTER WASTE ASSESSMENT FRAMEWORK

In the following section we outline the approach taken to assess disaster waste. Disaster waste can come in many forms (e.g., vegetation, packaging, unconsolidated sediment, construction and demolition, hazardous waste products) and be generated from a variety of mechanisms (e.g., collapse of structures, response activities) (Brown et al. 2011). We focus attention on the generation of building waste from multiple different volcanic hazards (tephra, PDC, and lava) as this is the most common and usually the most abundant waste generated from disasters (Reinhart and McCreanor 1999). We also consider clean-up requirements of the volcanic products themselves (tephra, PDC deposits, and lava). Although damage to horizontal infrastructure systems (e.g., tephra ingress into a stormwater system) is an acknowledged problem associated with volcanic eruptions (Wilson et al. 2012; Wilson et al. 2014) we do not address these in our approach due to high degrees of uncertainty associated with forecasting tephra ingress and blockage of these systems and potential reuse of buried networks once cleaned (such as storm and wastewater networks).

6.2.1 Overview

Scenario planning requires the use of a range of different scenarios that represent potential futures, which can be used to identify areas that require more specific planning (Bloom and Menefee 1994). It is important to note that the intention of using a scenario planning process is not to precisely forecast or predict the future, but to obtain a credible representation of the future (Bloom and Menefee 1994). This distinction is important because forecasting or predicting the future has often been associated with optimising decision-making and planning (e.g. identifying the single best decision given a certain probability distribution) (Walker et al. 2013). However, these approaches are highly reliant on accurate evaluation of uncertainties within the assessment, otherwise there is risk that the identified optimal plan is not actually the optimal plan. This is a major problem when planning for events that contain considerable degrees of uncertainty that cannot be accurately constrained within bounds that are reasonable for decision-making (Peterson et al. 2001). As discussed in Chapter 5, scenario planning is a useful approach for planning as it focuses on plausible futures and utilises collaborative and interdisciplinary approaches, which are important for identifying the potential diversity of issues that need to be managed (Bloom and Menefee 1994 recovery; van der Heijden 1997; Moats et al. 2008; Chermack 2004; Davies and Davies 2018). This is a fundamental aspect of disaster response and recovery planning because any plan produced must be flexible and adaptable to any event may arise, not just the most likely event (Walker et al. 2013). Thus, instead of focussing on identifying and constraining difficult to assess uncertainties, scenario planning provides a rationale for identifying a wide spectrum of plausible outcomes (Peterson et al. 2001; Chakraborty et al. 2011). Trying to optimise the plan is not important in this case, instead it is trying to make planning robust against these numerous plausible and diverse futures. Thus, the modelling framework developed in this chapter is intended to work in cooperation with scenario planning activities.

The proposed volcanic disaster waste scenario planning process used in this thesis builds on standard risk modelling concepts where a hazard model is used to assess damage to exposed assets (e.g. buildings) using vulnerability models. The benefit of taking this approach is that the process is generic and potentially transferrable to other communities. The first step of the volcanic disaster waste scenario planning process is to develop hazard scenarios that can be used in the disaster waste scenario planning process (will not be discussed in detail in this chapter, see Chapter 5 for details). The second step is to conduct a damage and/or impact assessment using the hypothetical hazard scenarios in conjunction with vulnerability models for affected assets. The purpose of this step is to classify and quantify expected damage (and thus waste generation) from each scenario (Section 6.2.2). The final step is a disaster waste assessment that estimates the quantity of waste (Section 6.2.3) and classifies clean-up management requirements (Section 6.2.4) from each scenario. The methodological advances presented in this chapter focus on the final step of this conceptual workflow (Figure 6.1).

6.2.2 Quantifying and classifying damage using scenarios

Damage from disasters can be assessed using vulnerability models that describe the damage or functional state that will result for a particular hazard intensity (Singhal and Kiremidjian 1996, Choi et al. 2004, Rossetto et al. 2013, Jenkins et al. 2014; Wilson et al. 2014; Tarbotton et al. 2015). Typically, geospatial analysis is conducted to overlay hazard, asset, and vulnerability data sets to assess the resulting damage. Although the process of assessing damage is largely generic, because building types and standards vary across the world, vulnerability model information needs to be specifically developed for the region under investigation and the intended use. For example, the EXPLORIS (Explosive Eruption Risk and Decision Support for EU Populations Threatened by Volcanoes: Spence et al. 2005) research project investigated the impacts of eruptions to communities surrounding Vesuvius in Italy (Zucarro et al. 2008), Teide on the Spanish island of Tenerife (Marti et al. 2008), and Soufriere on the French island of Guadeloupe (Spence et al. 2008). Local vulnerability assessments were undertaken for each community to inform the vulnerability components within each of those studies. In Germany, Leder et al. (2017) evaluated the damage and loss of residential building stock from a reawakening of Laacher See Volcano by using snow loading codes in the area. In New Zealand, building damage loss from an eruption scenario within the Auckland Volcanic Field has been assessed using RiskScape (Deligne et al. 2017a). RiskScape is widely used for modelling damage to New Zealand structures from a variety of different perils (e.g. earthquakes, tsunami, flooding), including volcanic hazards (tephra fall, PDC, lava flow, lahar, and edifice formation) and has been used in this work to investigate building damage in each of the hazard scenarios for the AVF (Deligne et al. 2017a). RiskScape contains a detailed building class database that is specific to Auckland buildings, which has been utilised in this work (discussed in section 6.4.3). The vulnerability module used within RiskScape is the chosen model used in this study (discussed in Section 6.4.4). The vulnerability module within RiskScape is still primitive, and mostly informed through the literature review from Wilson et al. (2014) and expert judgement (Deligne et al. 2017a). Damage states are used to characterise damage as these can be used to characterise and quantify debris generation (discussed in section 6.2.3).

6.2.3 Quantifying disaster waste

In order to quantify the waste that is generated from a hazard scenario, it is necessary to relate the damage that has been caused to a likely quantity of waste that is generated. A per unit generation approach has been used to do this across multiple different hazard types (Hirayama et al. 2010b; FEMA 2013a; Tanikawa et al. 2014; García-Torres et al. 2017) and is conceptually represented by equation 6-1:

$$TW_{ki} = PW_{kid} \times MS_{ki} \times N_{id} \tag{6-1}$$

Where 'TW_{ki}' is total building waste generated of material type k (e.g., wood, concrete) in building type i (e.g., residential, commercial). 'PW_{kid}' is the proportion of material stock that becomes waste of material type 'k', for building type 'i', at damage state 'd'. This can be determined by using pre-existing demolition data or heuristically quantifying the types of damage and waste generated at each damage state for different building types (we detail an approach for volcanic events in section 6.2.2). MS_{ki} is the total material stock of material type 'k', in building type 'i'. Material stock analysis can be used to estimate the quantity of different building materials within different asset types and when combined with expected damage estimates can be used to estimate the disaster waste profile likely to be generated under different scenarios (Tanikawa et al. 2014; García-Torres et al. 2017). The material stock can be obtained through detailed analysis of asset databases and quantifying the amount of different building materials within different building types (Kleemann et al. 2017). However, this often requires detailed building stock data (e.g., detailed building blueprints, previous demolition data) that are rarely publicly or rapidly available (Simpson et al. 2014). In lieu of detailed building stock information, some authors have made high level approximations of the main material constituents of different building types and building floor area (e.g., debris generated per square metre) (Hirayama et al. 2010b). 'N_{id}' is the number of buildings of type 'i' at damage state 'd'. This is obtained by the damage assessment, usually utilising fragility/vulnerability models with hazard scenarios. Summing for all material types, building types, and damage states will obtain a quantitative estimate for the total building waste generated.

Damage states are a method of classifying observed damage (undamaged to total collapse) after a disaster (Blong 2003a). They often contain qualitative descriptions and quantitative measures of damage sustained under different hazard intensities (Spence et al. 1996; Blong 2003b; Baxter et al. 2005; Jenkins et al. 2013, 2015; Hayes et al. 2019: Chapter 4). Thus, it is possible to envision the types of debris that could be generated at different damage states, particularly by investigating the damage generation mechanisms. To consider different modes of damage to a building, we break buildings down into six elements (Table 6.1) and estimate the proportion of waste generated to each building element at each damage state. Note, that we do not consider potential political or insurance related decisions that may influence the waste profile. For example, political leaders or emergency/recovery managers may determine some areas no longer appropriate for human occupation and order buildings demolished, regardless of the damage they sustained (Saunders and Becker 2015; Quigley et al. 2019). Insurers may also pay out for replacement of the entire building if it is deemed too expensive to repair or if the insurance contract is favourable towards replacement compared to repair (King et al. 2014). Both instances could potentially increase the quantity of waste that results from a disaster (Brown et al. 2011). However, while these factors are important considerations, we note that the required precision for disaster waste assessments for disaster waste management planning is typically at the order-of-magnitude scale (FEMA 2007; Tonkin & Taylor 2018).

Table 6.1: Building element class and examples of building components included

Building element class	Example of building components included
Roof (non-structural)	Roof covering, gutters, ceiling
Roof (structural)	Principle support beams, reinforced concrete
Walls	Wall cladding, structural supports
Flood	Floor and foundation
Fittings	Electrical sockets, air conditioning
Contents	Electrical appliances, sofas, carpet

6.2.4 Classifying disaster waste management in urban areas after volcanic eruptions

Disaster waste assessments in the literature end after quantifying the amount of waste that is to be produced. However, it is important to have a conceptual understanding of the context that disaster waste management must be conducted within during a disaster (Brown et al. 2011). For example, some areas may need to be cordoned whilst specialist crews and equipment can manage the disaster waste (e.g. where buildings need to be demolished). We are not aware of any studies that have attempted to classify different waste management requirements across an urban area to obtain insights into the spatial variability of disaster waste management for response and recovery planning purposes. Thus, we attempt to develop a conceptual framework that can be used for this purpose through literature review. The purpose of this is to broadly classify different approaches, considerations, and resource requirements of cleaning up different parts of the urban environment. In Table 6 of Hayes et al. (2015), a clean-up operation classification was developed to classify the different scales of tephra clean-up operations. For example, minor tephra clean-up operations tend to utilise street sweeper trucks to remove fine tephra coatings of roads, whilst major tephra clean-up operations require considerable coordination of numerous clean-up crews consisting of heavy machinery, dump trucks, and labourers. To construct the volcanic disaster waste classification framework, we used Table 6 of Hayes et al. (2015) as a starting point to classify different scales of clean-up and different management requirements. Case studies from Chapter 2 were then used to more holistically develop the conceptual framework beyond tephra clean-up and consider different types of waste generation mechanisms and their management requirements.

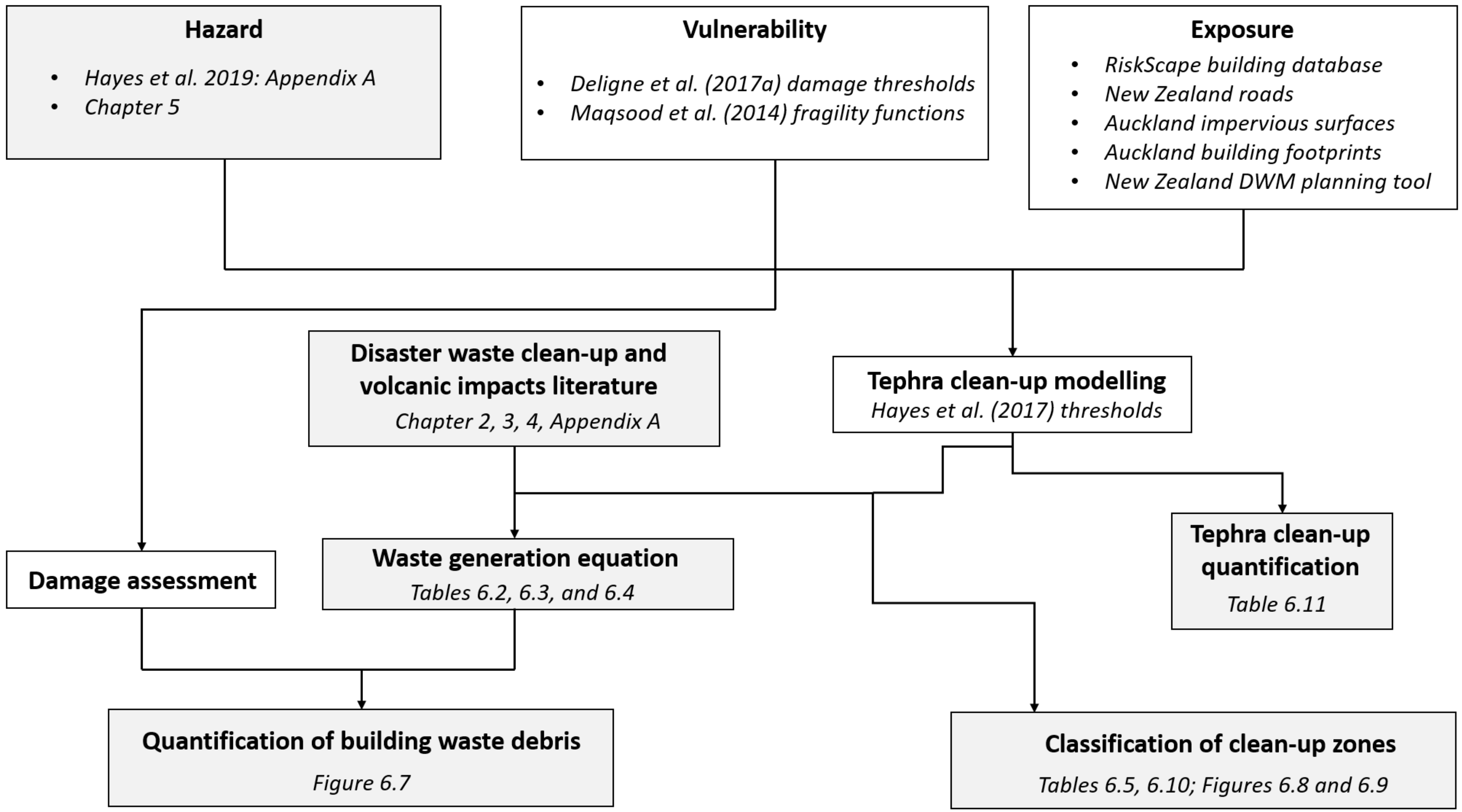

Figure 6.1: Workflow required to conduct a disaster waste assessment for volcanic events. Shaded grey boxes are specific contributions of this thesis.

6.3 RESULTS: VOLCANIC DISASTER WASTE ASSESSMENT FRAMEWORK

6.3.1 Quantifying disaster waste after volcanic events

Building debris generation

In the below subsections we estimate the proportion of waste generated at each damage state for tephra, pyroclastic density currents, and lava by using modified existing volcanic vulnerability models.

Tephra

Tephra can cause building debris generation through damage from static loading (e.g., roof collapse), contamination of building contents, and corrosion/abrasion of roof covers (Blong 1984). Table 6.2 presents an example damage state framework from Hayes et al. (2019), which assessed tephra fall impacts on timber-framed buildings from the 2015 Calbuco eruption, Chile. We use this as an example because each framework should be selected based on what is most appropriate for the study area context. For a property assigned DS0, we have assumed no waste will be generated other than cleaning up tephra. As the damage state increases, more aspects of the building are incorporated into the equation. For example, at DS4 considerable structural damage occurs, with at least one principle roof support and one wall collapsing. Therefore, we assumed that over 50% of the roof (both non-structural and structural components) will become waste. We also assume that between 10-100% of the fittings and contents will become waste as a result of the damage to the building and likely tephra contamination. At DS5, complete collapse of the structure occurs, and we assume 100% of the building and building contents will become waste.

Table 6.2: Linking tephra damage state to building debris generation for timber-framed buildings. Example damage state framework adapted from Hayes et al. (2019) (Chapter 4)

State	Description	Characteristics	Waste generation equation
DS0	No damage	- No damage caused	Deposit
DS1	Minor damage to non-structural elements	- Minor damage to roof covering (e.g., dents in metal sheeting, crack tiles). - Damage to fittings (e.g., air-conditioning units and appliances) - Contamination to contents	Deposit + Roof (non-structural) (1-10%) + Contents (1-10%) + Fittings (1-10%)
DS2	Moderate damage but vertical structure and roof supports intact	- As above - Bending or excessive (e.g., perforation, cracking) damage (with or without collapse) to up to half of roof covering, e.g., tiles, metal sheet. - Little to no damage to principal roof supports, i.e. rafters or trusses. - Damage to roof overhangs or verandas.	Deposit + Roof (non-structural) (1-50%) + Roof (structure) (0-1%) + Fittings (1-100%) + Contents (1-25%)
DS3	Severe damage to roof and supports	- As above - Bending or excessive (e.g., perforation, cracking) damage (with or without collapse) to over half of roof covering. - Damage to any single principal	Deposit + Roof (non-structural) (50-100%) + Roof (structure) (1-100%) + Fittings (1-100%) + Contents (1-50%)

State	Description	Characteristics	Waste generation equation
		roof supports and some damage to walls. - Severe damage or partial collapse of roof overhangs or verandas.	
DS4	Partial or total collapse of the roof and supports	- As above - Collapse of roof covering and any single principal roof support(s). - At least half of the external walls and/or internal walls deformed or collapsed.	Deposit + Roof (non-structural) (50-100%) + Roof (structure) (50-100%) + Walls (50-100%) + Fittings (1-100%) + Contents (1-100%)
DS5	Building collapse	- As above - Collapse of roof, principal roof supports and/or supporting external walls over more than 50% of floor area of building.	Deposit + Roof (non-structural) (100%) + Roof (structure) (100%) + Walls (100%) + Fittings (100%) + Contents (100%) + Floor (100%)

PDC

Damage caused by PDC can be a result of dynamic forces exerted on the structure and heat (Blong 1984; Baxter et al. 2005; Jenkins et al. 2013). Thus, the effects of PDCs on communities can be devastating, with extreme threat to life and severe impacts to the built environment. Areas heavily damaged by PDCs can be abandoned due to ongoing life safety risks posed by continued volcanic activity or due to the large-scale landscape changes drastically increasing the risk associated with potential cascading hazards, such as lahars (e.g., Soufrière Hills: Loughlin et al. 2002). This means there are limited documented case studies to review for understanding the issues associated with cleaning up following PDC inundation in urban environments. Famously, the town of Saint-Pierre, Martinique was destroyed by PDC activity from the 1902 Mt. Pelée eruption and was never restored entirely (some villages re-established in the decades following) (Scarth 1999). More recently, the city of Plymouth, Montserrat was abandoned after being inundated by PDCs from the eruption of Soufrière Hills from 1995-1999 (Kokelaar 2002). Major public works programmes have initiated as a result of PDC activity, notably following the 1991-1995 Unzen-Fugendake eruption, where sediment retention dams were constructed to manage future PDCs and associated sediment deposition to protect and allow reoccupation of neighbouring land (Ikeya 2008). Additionally, years after the Unzen-Fugendake eruption some areas affected by PDCs have been preserved in their damaged state as a memorial and tourist attraction, and roads affected by PDC had to be restored (Aota 2012). Therefore, we can assume a range of post-PDC management responses are possible, ranging from total abandonment to reoccupation, suggesting that areas affected by PDCs will require disaster waste clean-up of some sort but largely depend on the context (e.g., demand for land, sense of place, life safety risks, risk appetite, and economy) of the affected community.

For waste generation from PDC, we use the damage states used by Baxter et al. (2005) when classifying damage to buildings from pyroclastic surges from the Soufrière Hills eruption, Montserrat (Table 6.3). We note that waste may have been transported considerable distances away from the building due to becoming entrained within the PDC as it traverses the landscape (Baxter et al. 2005).

Table 6.3: Example PDC damage state framework based on Baxter et al (2005).

State	Description	Characteristics	Waste generation equation
DS0	No damage	- No or minimal ash penetration. Infiltration of ash due to window catch or frame in bad condition.	Deposit + Fittings (0-1%)
DS1	Light damage	- Broken windows - Limited fire damage to roof - Melted PVC guttering - Thin layer of ash inside	Deposit + Fittings (1-10%) + Roof (non-structural (1-10%) + Contents (1-10%)
DS2	Moderate damage	- Window and door frames imploded on side facing crater - Roof partially burned through from external heat flow - Deep layer of ash in rooms where penetration has occurred, fine layer only in remainder of building. - Combustion of furnishings by hot ash deposit. Complete combustion in rooms where fire occurs, part of roof burnt out from internal fire.	Deposit + Walls (1-25%) + Roof (non-structural (1-25%) + Fittings (1-25%) + Contents (1-25%)
DS3	Heavy damage	- All windows on side of volcano imploded, and windows on opposite sides blown out or outwards, including frames, roofs lifted off. - Missiles such as galvanised sheets and wood more abundant and gathered against walls facing crater. - Most trees and utility poles downed. Fences and posts pushed over - Widespread internal fire with ash deposit throughout, roof burnt	Deposit + Roof (non-structural) (25-100%) + Roof (structural) (25-100%) + Floor (50-75%) + Fittings (50-100%) + Walls (1-25%) + Contents (50-100%)

State	Description	Characteristics	Waste generation equation
		away by internal fires, radiant heat from deposit, or heat transfer from flow	
DS4	Partial devastation	- As above, but loss of parts of external and/or internal walls. - Large single or multiple small missile impacts to wall facing volcano, most or all of roof missing from fire or lifting off of non-RC roofs. - No lightweight buildings left standing. Abundant missile debris.	Deposit + Contents (100%) + Roof (non-structural) (50-100%) + Roof (structure) (50-100%) + Fittings (100%) + Wall (25-75%) + Floor (50-100%)
DS5	Complete devastation	- Walls removed, only parts or none of the structure still standing. - Multiple large missile impacts. - Complete devastation from heat, dynamic pressure and missiles - Ground scoured with little deposit or remaining debris.	Deposit + Contents (100%) + Roof (structural) (100%) + Roof (non-structural) (100%) + Fittings (100%) + Floor (100%) + Wall (100%)

Lava flow

The damage caused by lava flows to buildings can be summarised as being caused by (Blong 1984; Harris 2015; Jenkins et al. 2017): 1) gravitational-mechanical or static load forces; 2) dynamic-mechanical forces; 3) permanent inundation by lava; and 4) thermal and thermo-chemical effects. However, even if a building remains structurally sound after lava flow inundation, it is likely that all the economic value of an inundated buildings will be lost (Jenkins et al. 2017). Thus, the vulnerability/fragility of buildings to lava is typically treated as binary (i.e. total loss if exposed to lava) in the risk assessment literature (Deligne et al. 2017a). Although the building might be a total loss, it is a more complex matter to relate this to a quantifiable estimate of the disaster waste that is generated. Lava flows can retain heat for up to decades (Williams and

Moore 1983), which can make removing the lava and entrapped buildings logistically challenging. The question then becomes how to treat land inundated by lava flows. A common response is to abandon the land, but in some situations, communities have removed small parts of lava that has inundated towns or cities once the lava has cooled sufficiently (Williams and Moore 1983). Here we assume that waste entrained within the lava flow will be removed eventually, but that total loss occurs to a building upon exposure (Table 6.4).

Table 6.4: Lava flow damage state framework used in this study.

State	Description	Characteristics	Waste generation equation
DS0	No damage	No damage caused	None
DS5	Complete loss	- Burial/inundation - Cracks to wall and/or roof structures - Fire damage - Damage from explosions	Contents (100%) + Roof (structural) (100%) + Roof (non-structural) (100%) + Fittings (100%) + Floor (100%) + Wall (100%)

6.3.2 Clean-up zoning framework

We have developed a clean-up zoning framework for use characterising disaster waste management requirements under different land use typologies for volcanic eruptions based on international disaster waste literature and examples of communities effected by volcanic eruptions (Table 6.5).

No clean-up

The ‘no clean-up zone’ is an area where no coordinated clean-up efforts are required. This means that changes to usual maintenance and waste collection processes is unlikely to be necessary.

Table 6.5: Clean-up zone framework

Clean-up zone	Description	Area	Land use		
			Residential	**Commercial/industrial**	**Open space / fields**
0	No clean-up	Property	No clean-up necessary		
		Street			
1	Minor	Property	Residential property owners self-manage. Areas that were under evacuation may require careful disposal of putrescible waste products (e.g., rotten food) Volunteer workforces may need to be managed.	Parking restrictions may be required. Contractors potentially required at industrial sites to handle contaminated waste products. Areas that were under evacuation may require careful disposal of putrescible waste products (e.g., rotten food)	Paved surfaces cleaned, may require council workers/contractors. Grassed or vegetated areas do not require clean-up
		Street	Road sweeper trucks to clean roads of tephra, followed by road washing with sprinkler trucks to remove remaining residue. Care required to ensure tephra does not enter the stormwater system.		
2	Moderate	Property	Residential property owners will require assistance with removal. Clean-up should be coordinated to increase efficiency, with residential property owners placing tephra at the kerbside for collection during road clean-up.	Same as for minor clean-up. Heavy earth-moving machinery required to clear rubble and tephra deposits. Specialised cleaners may be required at sites where contamination of industrial chemicals has occurred.	

			Volunteer workforces likely need to be managed. Potentially minor – moderate building damage (e.g., gutters collapse, dents on roofs)		
		Street	Heavy earth-moving machinery may be required to move rubble and debris from roads. Bulk unconsolidated sediment (e.g., tephra) removed from roads using heavy earth-moving machinery (e.g., graders, bulldozers, diggers), followed by sweeper trucks and road washing with sprinkler trucks to remove remaining residue.		
3	Major	Property	Waste likely to be highly mixed. Clean-up priority to remove health and safety risks. Full clean-up may require insurance evaluations. Access restrictions may be necessary for health, safety and security. Household hazardous waste programme potentially required for condemned houses.	Waste likely to be highly mixed. Specialised machinery required to remove waste. Access restrictions may be necessary at some sites for health, safety and security. Hazardous waste products may require careful and specialised handling.	Paved surfaces cleaned, may require council workers/contractors. Removal and/or stabilisation of unconsolidated sediments required.
		Street	Heavy earth-moving machinery likely to be required to move rubble and debris from roads. Bulk unconsolidated sediment (e.g., tephra) removed from roads using heavy earth-moving machinery (e.g., graders, bulldozers, diggers), followed by sweeper trucks and road washing with sprinkler trucks to remove remaining residue.		
4	Major land remediation	Property	Substantial damage to land that requires remediation works before returning to usable state. It may be necessary to conduct activities to remove human health and environmental hazards (e.g., downed power lines, sediment runoff control).		
		Street			

Minor clean-up

Minor clean-up areas after volcanic eruptions will be those affected by relatively low deposition of tephra (1-10 mm) (Hayes et al. 2015). Roads are likely to require elevated levels of maintenance through cleaning to remove tephra from obscuring road markings and reducing traction (Blake et al 2016; 2017b). Such operations are regularly undertaken in Kagoshima City, Japan from ongoing eruptions at Sakura-Jima volcano (Durant et al. 2001; Ishimine et al. 2012; Hayes et al. 2015). Road cleaning (if required) can be achieved using street sweepers to remove tephra and washing of the roads using sprinkler trucks and is a common clean-up process undertaken in areas where low accumulations of tephra occur 1-10 mm (Figure 6.2) (e.g., Portland, USA - Blong 1984; Kagoshima City, Japan - Hayes et al. 2015; Villa la Angostura, Argentina - Hayes et al. 2019c: Chapter 3). Care will be required to minimise tephra ingress into the stormwater system, because even minor amounts of tephra can cause blockages, potentially leading to localised flooding (Blong 1984; Johnston 1997; Wilson et al. 2012). For example, in Portland, USA, following tephra deposition from Mt. St. Helens in 1980, workers placed sandbags over stormwater drains prior to clean-up crews arriving to begin street clean-up. It is most likely that property owners will be able to self-manage clean-up in these areas (Hayes et al. 2015). Advice and directions will need to be disseminated to the public regarding appropriate disposal of tephra, particularly not to place tephra into the stormwater system (Stewart et al. 2016).

Moderate clean-up

Moderate clean-up is where tephra accumulations are likely to exceed the capacity of property owners to remove and dispose of tephra by themselves (Hayes et al. 2015). Therefore, coordinated clean-up of both the street areas and private properties in these areas will be necessary for an efficient clean-up response (Hayes et al. 2015).

Figure 6.2: Examples of minor clean-up zone: Clean-up following the 2012 Te Maari eruption, New Zealand (Photos: Grant Wilson)

Disruption to ground transportation is likely and it is possible that in places heavy earth-moving machinery will be necessary to grade tephra to the sides of the road to restore road functionality (Figure 6.3) (Blong 1984; Wilson et al. 2012; Hayes et al. 2015; Blake et al. 2016; 2017a). Heavy earth-moving machinery had to be used in Yakima where approximately 50-80 mm of tephra accumulated following the 1980 eruption of Mt. St. Helens (Blong 1984). Volunteer groups may also be active in the clean-up of these areas, such as during the clean-up of Guatemala City after the 2010 Pacaya eruption (Wardman et al. 2012). Careful organisation and management of any volunteer groups that assist with clean-up activities will be necessary to ensure their health and safety and to make sure that they are operating in a coordinated manner for clean-up operation efficiency (Hayes et al. 2015).

Some minor to moderate building damage (e.g., DS1-DS2) may be possible and these waste streams may require management (Chapter 4; Appendix A). Potential for contamination at industrial sites (e.g., tephra loading damage to industrial storage tank roofs: Milazzo et al. 2013), may require specialised clean-up (Young et al. 2004).

Figure 6.3: Example of moderate clean-up zone: A-C) Approximately 10-30 mm of tephra from the 2015 eruption of Calbuco volcano, Chile, in Junín de los Andes, Argentina, April 2015 (Photos: Junín de los Andes Bomberos), D-E) Clean-up of 100-200 mm in Ensenada, Chile, following the 2015 Calbuco eruption (Photos: Chilean Ministro Obras Públicas); F) Clean-up in Jacobacci, Argentina, following the 2011 Cordón-Caulle eruption (Photo: Aileen Rodriguez). Photos D-F are at the boundary between moderate-major disaster waste clean-up.

Major clean-up

We define major clean-up zones as those where considerable mixing of waste occurs (e.g., due to considerable damage to the built environment) and carefully managed clean-up operations are required. These areas may require access restrictions in places for health and safety, and law and order (Brown et al. 2010; Chang et al. 2014). For example, access restrictions were put in place in Ensenada, Chile, after the 2015 eruption of Calbuco due to the potential for PDCs to affect the area (Hayes et al. 2019c: Chapter 3; Hayes et al. 2019a: Chapter 4; Hayes et al. 2019b: Appendix A). Access restrictions were also eventually placed in Rabaul Town, where there were reports of substantial damage to buildings and contents beyond that from the volcanic eruption due to looting (Blong and McKee 1995).

Due to the high levels of damage, these areas will typically require demolition activities and associated specialised personnel and equipment (Brown et al. 2011). There may be instances where waste has been transported across boundaries (either property or political). For example, lahars from the 2015 Calbuco eruption, some buildings and bridges in Rio Blanco, Chile, were lifted and transported by the force of the lahar (Figure 6.4) (Chapter 4; Hayes et al. 2019b: Appendix A). Where waste has been transported across boundaries, there may be a need to ascertain ownership of the waste before it can be removed (e.g., for insurance: Brown et al. 2011).

Damage at industrial sites and contamination of industrial storage tanks and facilities may occur, and specialised cleaning will be required due to potential for exposure of workers to hazardous materials and environmental consequences of spillages (Young et al. 2004). If evacuation is unsuccessful prior to the eruption, human remains may be present and will require careful management (Morgan et al. 2006; Leditschke et al. 2011; Wagner 2014; Cordner and Ellingham 2017).

It is conceivable that areas we designate as major clean-up zones will not be fully restored, e.g., due to the cost being prohibitively high, changed land-use (planned or unplanned during the recovery), or ongoing life safety risks (e.g., Plymouth, Montserrat: Kokelaar 2002; southern parts of Rabaul Town, Papua New Guinea: Johnson 2013). These decisions are likely to be context specific and deeper consideration of this is beyond the scope of this work.

Figure 6.4: Examples of major clean-up areas. A) Rabaul, Papua New Guinea after the 1994 eruption of Tarvurvur and Vulcan (Photo: AusAid), B-D) Chaiten Town, Chile, following lahar inundation from the 2008 Chaiten eruption (Photos: Thomas Wilson), E) Rio Blanco, Chile, following the 2015 Calbuco eruption (Photo: Chilean Ministro Obras Públicas)

Major land remediation

As a result of volcanic eruptions there may be areas that were previously developed that require substantial land remediation before that land can be restored to the previous land use (Figure 6.5). We consider land remediation to be areas where large scale geotechnical investigations and/or engineering projects would be required, such as installation of sediment and flood control structures (e.g., Uchida et al. 2009), land stabilisation following volcanic cone or crater construction (e.g., Morgan 2000) and/or eruption induced land-deformation (Hirose and Tajika 2000; Miniami et al. 2001; Tiwari et al. 2001), and development on or removal of lava flows (Williams and Moore 1983). Areas continuously affected by acute life-threatening volcanic hazards (e.g., PDC, lahars) may also fall within this category and so detailed assessments of life safety risks may also be required.

Note, that we not making a judgement on whether these areas should or should not be remediated. That will be the prevue of local authorities and communities and beyond the scope of this work. Our point is to highlight areas that will require substantial remediation efforts if they are to be reoccupied.

Figure 6.5: Example of area requiring considerable land remediation if ever to be restored to previous land use: Lava within fissure 8 crater and cone, Hawaii, USA, September 6, 2018 (Photo U.S. Geological Survey)

6.4 CASE STUDY: AUCKLAND VOLCANIC FIELD (AVF)

6.4.1 Overview of the AVF

The Auckland Volcanic Field (AVF) is a monogenetic volcanic field that represents a high risk due the highly urbanised city of Auckland built on top of it (Figure 6.6). An eruption within the AVF has an annual exceedance probability of 0.03 – 0.08 (Molloy et al. 2009; Hurst and Smith 2010; Leonard et al. 2016) and could disrupt and severely damage Auckland infrastructure (Johnston et al. 1997; Deligne et al. 2017b; Blake et al. 2017a) with direct losses reaching into the billions of dollars (Magill et al. 2006a; Deligne et al. 2017a). Therefore, the AVF is an ideal environment to test the utility of the approach developed in this paper to assess disaster waste management requirements in a complex urban environment. In the next sections we detail how we utilised the conceptual framework to assess disaster waste management requirements in Auckland after potential AVF eruptions.

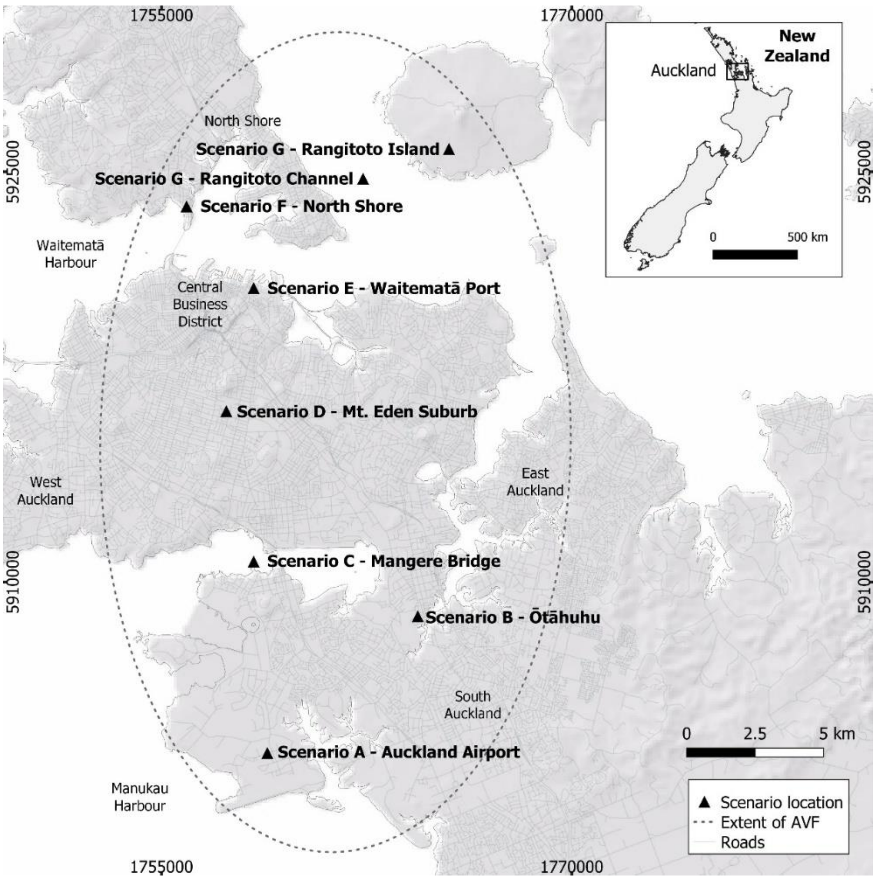

Figure 6.6: Auckland, New Zealand, and scenarios used in this work. AVF extent from Runge et al. (2015)

6.4.2 Hazard scenarios

We used 8 hypothetical eruption scenarios as our hazard scenarios (Table 6.6; Hayes et al. 2018). The scenarios were designed for the specific purpose of evaluating a range of credible impacts to Auckland following eruptions within the Auckland Volcanic Field. A summary of the eruption scenarios is presented in Table 6.6 and full documentation of the scenario development process and outcomes can be found in Hayes et al. (2018) and Chapter 5 of this thesis.

Table 6.6: Summary of the DEVORA Scenarios (Hayes et al. 2018: Appendix C; Chapter 5)

Scenario	Volume	Duration of detected precursory unrest	Duration of eruption	Eruption style(s)
A – Auckland Airport	$1.9x10^{-2}$	8 days	4 days	Phreatomagmatic
B - Ōtāhuhu	$3.4x10^{-2}$	13 days	32 days	Complex – phreatomagmatic to magmatic explosive and effusive
C – Māngere Bridge	$1x10^{-1}$	23 days	32 days	Complex – phreatomagmatic to magmatic
D – Mt. Eden Suburb	$1.2x10^{-1}$	45 days	320 days	Magmatic
E – Waitematā Port	$1.2x10^{-2}$	3 days	27 days	Magmatic to Phreatomagmatic to magmatic
F – Birkenhead	$1.9x10^{-2}$	15 days	160 days	Phreatomagmatic to magmatic
G – Rangitoto Channel	$1.4x10^{-2}$	10 days	8 days	Surtseyan
H – Rangitoto Island	$1.8x10^{-2}$	660 days	104 days	Phreatomagmatic to magmatic

6.4.3 Material stock of Auckland buildings

There is no detailed publicly available material stock information for Auckland buildings, so we are reliant on baseline estimates of building materials in the New Zealand Disaster Waste Management Planning Tool and associated scoping studies (Stantec 2017; Tonkin & Taylor 2018) (Table 6.7). Fundamentally, this information is based on preliminary data from the demolition of buildings in Christchurch, New Zealand following the Canterbury Earthquake Sequence, which indicates that for a completely demolished building approximately 1 tonne of building waste is generated per m^2 of floor area (Stantec 2017). This estimate is likely to vary between building types, but it is the best information presently available. Thus, we have assumed total material stock within buildings amounts to 1 tonne/m^2 of floor area and is distributed as per Table 6.7.

The RiskScape building database contains detailed building inventory information (e.g., building class, replacement costs, height) for New Zealand, is used to determine the location and types of buildings in Auckland. The RiskScape building database uses more building classes than those described in the New Zealand Disaster Waste Management Planning Tool, so we had to link the RiskScape building classes to an equivalent building type in the New Zealand Disaster Waste Management Planning Tool (Table 6.7).

6.4.4 Damage assessment

Within the vulnerability module of RiskScape, each of the volcanic hazards has specific rules or relationships that are used to evaluate the damage that occurs to buildings at different hazard intensities (Table 6.8; Deligne et al. 2017a). For most perils, RiskScape uses hazard intensity thresholds that correspond to different levels of damage (Table 6.8). However, for tephra fall, RiskScape uses the tephra vulnerability model from GAR 2015, which utilises damage ratios as a function of total replacement cost (Maqsood et al. 2014). To obtain consistent results when assessing damage across each of the volcanic hazards it is necessary to convert the damage ratios into a corresponding damage state. To do so, we identified damage ratio thresholds that would signify each damage state (Table 6.9). We also include ballistics within the tephra category. If a ballistic is modelled to land coincident with a building footprint, and the impact energy is sufficient to perforate the roof material (based on Williams et al. 2018). we assume at minimum a DS2 on the tephra damage state framework. As used in Deligne et al. (2017b), we assume a wet tephra deposit density of 1500 kg/m^3 to convert tephra thickness to loading.

Table 6.7: Proportion of building mass made up of different building materials and building elements (based on baseline total building materials in Stantec 2017)

Building type	RiskScape building classes	Building element	Material			
			Wood	Concrete	Metal	Other
Typical residential building: timber cladding with steel roof	5, 11	Roof (non-structural)	0	0	0.05	0
		Roof (structural)	0.025	0	0	0.01
		Walls	0.175	0	0	0.01
		Floor	0.025	0.6	0	0.01
		Fittings	0	0	0	0.05
		Contents	0.025	0	0	0.02
		Total building	0.25	0.6	0.05	0.1
Typical residential building: Brick cladding with tile roof	9	Roof (non-structural)	0	0.18	0	0
		Roof (structural)	0.005	0	0	0.005
		Walls	0.04	0.45	0	0.005
		Floor	0	0.27	0	0.005
		Fittings	0	0	0	0.025
		Contents	0.005	0	0	0.01
		Total building	0.05	0.9	0	0.05
Typical commercial style building	1, 2, 4, 6, 7, 10,	Roof (non-structural)	0	0	0.005	0
		Roof (structural)	0	0.12	0	0.025
		Walls	0.01	0.3	0.025	0.025
		Floor	0	0.18	0.02	0.025
		Fittings	0.02	0	0	0.125
		Contents	0.07	0	0	0.05
		Total building	0.1	0.6	0.05	0.25

Table 6.8: RiskScape building damage states for non-tephra volcanic hazards (from Deligne et al. 2017a)

Hazard	Hazard intensity metric	Hazard intensity	Damage state
PDC	Dynamic pressure (kPa)	< 1	0
		1-10	2
		10-25	4
		>25	5
Lava	Thickness (m)	0	0
		>0	5
Edifice	Height (m)	0	0
		>0	5

Table 6.9: Assumed damage state from tephra hazard intensity (based on Maqsood et al. 2014 and Deligne et al. 2017a)

RiskScape Building Class	Tephra thickness (cm)	Tephra loading (kPa)	Damage state
1, 2	< 19	<3	0
	20 - 34	3 - 5	1
	35 - 54	5 - 8	2
	55 - 74	8 - 11	3
	75 - 102	11 - 15	4
	>102	>15	5
4, 10, 6, 7	< 27	<4	0
	28 - 40	4 - 6	1
	41 - 48	6 - 7	2
	49 - 75	8 - 11	3
	76 - 102	11 - 15	4
	> 102	>15	5
5	< 14	<2	0
	15 - 20	2 - 3	1
	21 - 34	3 - 5	2
	35 - 40	5 - 6	3
	41 - 74	6 - 11	4
	> 75	>11	5
9	< 14	<2	0
	15 - 20	2-3	1
	21 - 34	3-5	2
	35 - 40	5-7	3
	41 - 74	7-11	4
	> 75	>11	5
11	< 14	<2	0
	15 - 20	2 - 3	1
	21 - 34	3 - 5	2
	35 - 40	5 - 6	3
	41 - 74	6 - 11	4
	> 75	>11	5

6.4.5 Quantifying disaster waste generation

Once damage states were assigned to each building, we utilised the conceptual approach outlined in Section 6.2. We used the equations contained within Tables 6.2, 6.3, and 6.4 to determine the quantity of debris generated from building damage. To supplement building debris estimates we also quantified the expected tephra that would require removal. To determine the quantity of tephra requiring removal we used the approach of Hayes et al. (2017). This approach utilises Auckland specific tephra clean-up thresholds that initiate different tephra clean-up responses. We refer the reader to Hayes et al. (2017) for further details.

6.4.6 Mapping clean-up zones

To utilise the clean-up zoning framework presented in section 6.3.2, we used geospatial analysis to map the zones for each eruption scenario on a 500x500 m grid across the AVF. To do so, we related hazard intensity within each 500x500 m polygon to the corresponding clean-up zone (Table 6.10). This is specifically considered for Auckland, New Zealand, although many of these thresholds may also be relevant for other similar urban areas around the world. Below we explain our rationale for designation of the thresholds.

Lava flow and edifice affected areas

We assume that any area within 500 m of a vent will require substantial land remediation (Table 6.10). This is because of heavy deposition of volcanic materials, edifice formation (e.g., building of a scoria cone: Williams and Moore 1983), land deformation (e.g., Hirose and Tajika 2000), and potential long-term subsidence (e.g., Lorenz 2007). We also assume that any area exposed to lava flow will require substantial remediation (e.g., flattening of the ground) before it could be rebuilt on or lava to cool before it can be removed. All areas outside of these hazard areas we assume can be cleaned in Auckland.

PDC affected areas

In other localities around the world, areas affected by PDC have been abandoned (e.g. Plymouth, Montserrat). We deem this as unlikely in Auckland due to the land scarcity and that in most cases once an eruption has ceased it is unlikely that a future eruption will occur in the same locality, mitigating potential life safety risks characteristic of other areas around the world affected by PDC. However, we acknowledge that if an eruption were to be very long lasting (e.g., multiple years), it is possible that areas within a several kilometres may be excluded for life safety reasons. Thus, the uncertainty associated with whether an eruption has ceased may be an important consideration in whether clean-up occurs within these areas. We consider that any areas affected by PDC will be classified as a moderate clean-up zone at a minimum due to the likelihood of substantial deposition of tephra and moderate building damage. We use 10 kPa as a threshold between moderate and major clean-up zones as this is the threshold used to define the difference between buildings of DS2 and DS4 within RiskScape (Deligne et al. 2017a).

Tephra fall affected areas

Areas affected by tephra deposition are sectioned into four different zones, based on the tephra clean-up thresholds developed specifically for Auckland in Hayes et al (2017).

Table 6.10: Hazard typology and intensity used to map the clean-up zones

Volcanic hazard	Hazard intensity	Clean-up zone
Within 500 m of vent / edifice	Exposure = yes	Remediation
Lava	Exposure = yes	
Tephra	< 1 mm	No coordinated clean-up
	1 – 10 mm	Minor clean-up
	> 10 – 200 mm	Moderate clean-up
	> 200 mm	Major
PDC	≤ 10 kPa	Moderate
	> 10 kPa	Major

6.5 CASE STUDY MODELLING OUTPUTS

6.5.1 Building debris

Building debris generation quantities for each scenario are presented in Figure 6.7. These results show considerable variability of the waste quantity across the scenario suite. The scenario with the greatest quantity of building debris generated is Scenario E - Waitematā Harbour (~11-14 million tonnes). We estimate ~5,000 - 130,000 tonnes for Scenario H - Rangitoto Island, the smallest estimate in our scenario suite. The median quantity of building waste generated across the scenarios falls into the 2-3 million tonnes range.

The building waste profile of the scenarios does not substantially change between eruption scenarios. Concrete is the major constituent waste product in each scenario, often exceeding 50% of the building waste profile measured in tonnes. Approximately 10-15% of the waste tonnage was classified as wood, 4-5% for metal, and 20-35% other.

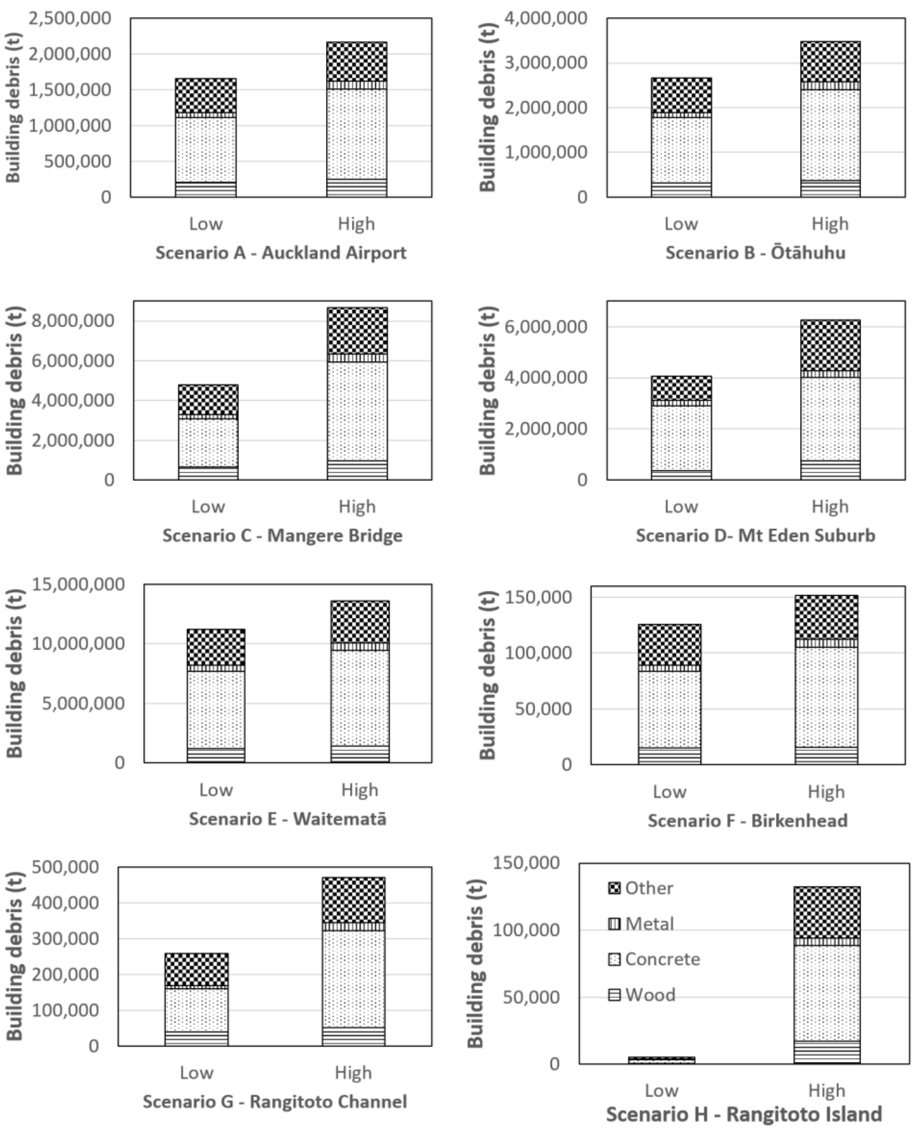

Figure 6.7: Tonnes of debris estimated for each DEVORA eruption scenario

6.5.2 Tephra removal

Considerable quantities of tephra will also need to be managed following an AVF eruption (Table 6.11). The quantity of volcanic products is likely to far exceed the quantity of building waste.

Table 6.11: Estimated quantity of tephra requiring removal. Tephra mass assumes deposit bulk density of 1500 kg/m^3. Scenario C - Māngere Bridge volume from Hayes et al. (2017).

Scenario	Tephra mass (tonnes) x10^9	Tephra volume (m^3) x10^6
A - Auckland Airport	2.8	1.9
B - Ōtāhuhu	4.1	2.7
C - Māngere Bridge	12	8
D - Mt. Eden Suburb	16	10
E - Waitematā Port	6.3	4.2
F - Birkenhead	2.3	1.6
G - Rangitoto Channel	1.5	1
H - Rangitoto Island	5.2	3.5

6.5.3 Clean-up zones

The geographical spread of clean-up zones for the DEVORA Scenarios are presented in Figure 6.8. Major clean-up of commercial and industrial areas is required for scenarios A, B, C, D, E, and to a lesser extent F. Scenario D appears to require the most substantial clean-up of residential areas. Clean-up for scenarios G and H are the least severe of the entire suite, with minor to moderate zones assigned to built-up areas along the eastern coastline. Areas that require land remediation are comparatively small compared to wider clean-up areas.

6.5.4 Cumulative evolution of clean-up zones during an eruption scenario

Eruptions within the AVF have the potential to have multiple eruptive phases and potentially last from a few days to multiple years. The DEVORA Scenarios included a spatio-temporal component to consider the potential evolution of an eruption sequence (Hayes et al. 2018). Thus, it is likely that clean-up zones will change as an eruption progresses through time. We use Scenario D – Mt. Eden Suburb to explore the potential evolution of clean-up zones through an eruption sequence (Figure 6.9). Here it is assumed no clean-up is taking place as the eruption progresses.

The area near the breakout of a fissure at the beginning of the eruption scenario is immediately classified in the remediation zone, and as lava inundates other areas further through the eruption sequence some areas change from moderate-major clean-up zones to requiring remediation. Due to proximity to the vent and the associated evacuation, it is unlikely that any mitigation activity (e.g., tephra removal from roofs) will be undertaken in areas within 5 km of volcanic activity due to Auckland Emergency Management evacuation policy (Auckland Civil Defence and Emergency Management 2015). However, it is likely that outer regions may conduct clean-up of tephra. As the eruption scenario progresses through time, multiple tephra depositions occur in a variety of directions due to wind direction changes, which leads to much of metropolitan Auckland requiring clean-up activities. However, not all areas will need to conduct these simultaneously but will require repositioning of equipment and staff.

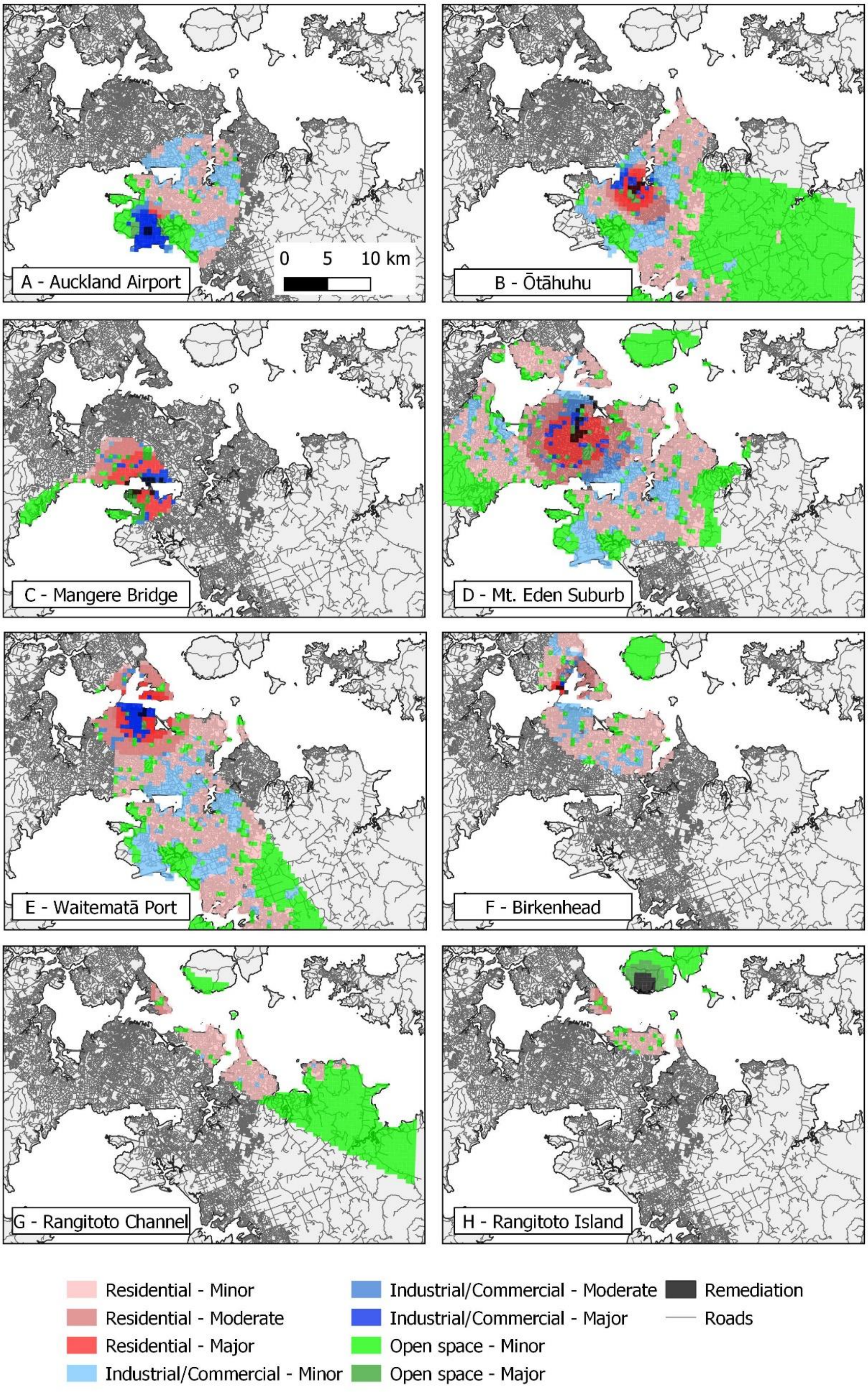

Figure 6.8: Clean-up zones for the DEVORA Scenarios. Roads added as proxy for population density

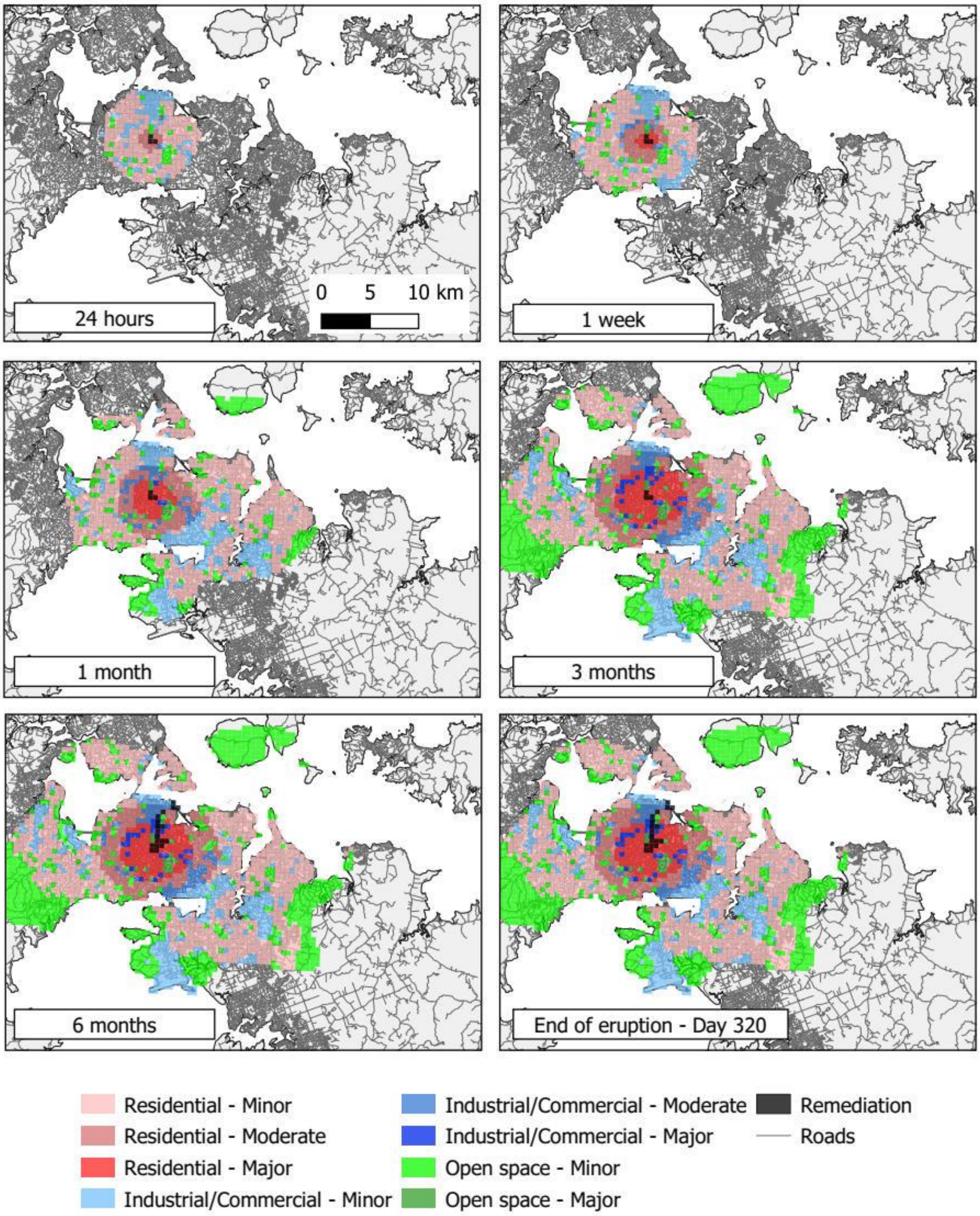

Figure 6.9: Evolving clean-up zones throughout the course of the Mt. Eden Suburb eruption scenario.

6.6 DISCUSSION

6.6.1 Modelling outputs and limitations

General considerations

We are unaware of any publicly available estimates of building waste quantities for areas affected by volcanic eruptions to compare our model outputs against. However, our results appear well aligned with other disaster types (Figure 6.10). For example, approximately 8000 homes and 1400 commercial properties required demolition following the Canterbury Earthquake Sequence (CES), New Zealand, resulting in an estimated 4 million tonnes of building debris and another 4 million tonnes of horizontal infrastructure waste (Brown and Milke 2016). Approximately 18,000 buildings required demolition after the 2009 L'Aquila earthquake in Italy, producing an estimated 4 million tonnes of waste (Brown and Milke 2016). The Japanese Government estimated 27 million tonnes of rubble was removed from the Japanese prefectures of Iwate, Miyagi, and Fukushima as a result of the 2011 Tōhoku earthquake and tsunami (Tanikawa et al. 2014). A subsequent analysis by Tanikawa et al. (2014) using a similar conceptual approach to the one conducted in this work estimated 31 million tonnes for those same prefectures and 34 million tonnes for all affected prefectures (estimates include debris from buildings and roads). A priority for future work is greater reporting of waste generated from volcanic eruptions, to build an evidence base and to allow evaluation of our approach.

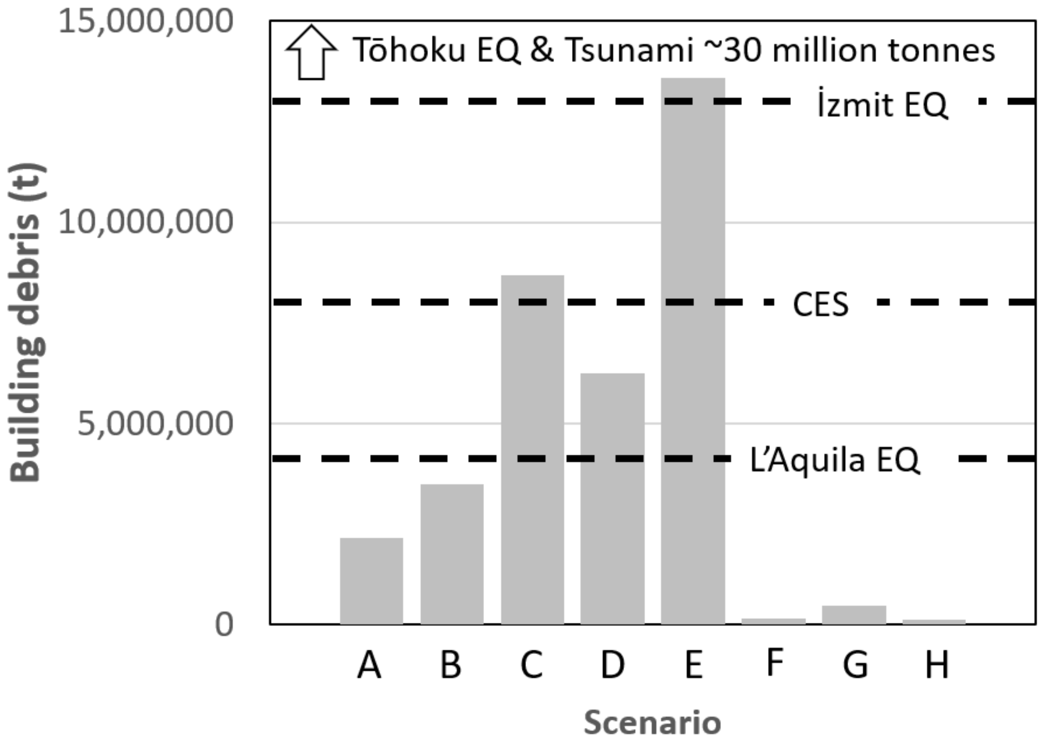

Figure 6.10: Comparing model outputs (maximum estimate) with high profile disasters. L'Aquila, Italy - 2010, and Canterbury Earthquake Sequence (CES), New Zealand – 2010-11 data from Brown and Milke (2016), İzmit, Turkey – 1999 data from Baycan (2004), and Tōhoku earthquake data from Tanikawa et al. (2014).

The approach used here has identified important management requirements that may potentially manifest during a future AVF eruption, such as large quantities of highly mixed waste streams. This is an important finding because it highlights the importance of more detailed research and planning on how to manage these issues specifically. For example, substantial waste is likely to be located within challenging to manage areas due to uncertainty associated with ongoing eruptive activity and associated hazards, so identifying protocols and re-entry criteria is important. From this perspective, we consider our approach useful for pre-event contingency and recovery planning. However, as the approach is simple and relatively quick to undertake, it could also be utilised as a rapid impact assessment post-eruption to get an early first order estimate of the potential waste generated from an eruption. This would provide useful information to emergency managers to identify resource requirements and allocation of resources to specific areas affected by the eruption.

Tolerance and capacity to manage tephra deposits after volcanic eruptions will differ across different social contexts (e.g., reliance on tourism trade, public health standards), environmental conditions (e.g., dry and windy conditions causing remobilisation), land use (e.g., agricultural, urban), and/or frequency of tephra fall exposure (Sword-Daniels et al. 2014; Hicks and Few 2015; Armijos et al. 2017). The assumptions made in the modelling undertaken in this work may not be appropriate for other contexts and specific consideration of the above factors will be necessary.

Case study specific considerations

In this assessment we have not included consideration for any decision-making that may occur. For example, an insurance provider may determine that buildings at a damage state of 4 are uneconomical to repair and are instead demolished. Similarly, political decisions on the restoration of some areas may result in some buildings being demolished when the physical damage to the individual building may not be considerable. Both situations would mean our approach would underestimate the total volume. It is also possible that mitigation actions could be taken before a building is affected by an eruption to reduce the waste produced. For example, it is common that contents or hazardous products are removed from areas in lava flow pathways. For at least Scenario D - Mt Eden Suburb it would be credible that some of the buildings in the lava flows pathway could have some contents removed, which would reduce the total estimated waste produced. A useful future development would be to use scenarios to explore different disaster waste management decision pathways to identify the most effective and efficient waste management methods under different disaster scenarios.

The building waste profile does not substantially change between scenarios in the Auckland case study application. This could be due to the crude measures of material stock used in this analysis. Material stock information is used that is based upon rules-of-thumb estimates used within the New Zealand Disaster Waste Management Tool, as this is the best information currently available. A detailed material stock analysis (e.g., Kleemann et al. 2017) would be of considerable value to enhancing the accuracy of this work.

6.6.2 Disaster waste management for AVF eruptions

In this paper we have developed the first disaster waste modelling framework for volcanic eruptions that can be used to strategically identify important planning considerations for disaster waste management in complex volcanic risk environments. A future AVF eruption is likely to differ from those scenarios presented in this thesis. However, by using a variety of scenarios we can identify generic issues that are likely to be experienced during a future AVF eruption, which allows for identifying strategic areas of contingency planning required. Using the results produced in this chapter, it would be possible to bring together the diverse set of stakeholders involved with disaster waste management (e.g. solid waste managers, contaminated land managers, emergency management officials, recovery managers, public health officials) to collaboratively develop plans that are robust against the diverse scenarios that may occur during a future AVF eruption and identify future research activities (Beaven et al. 2016). This approach is a common feature of scenario-based planning (Bloom and Menefee 1994; Keough and Shanahan 2008). Thus, the purpose here is not to precisely forecast specific quantities of waste, but to develop a modelling framework that can facilitate a credible assessment of waste management issues, which acts as a collaborative tool for identifying specific research and planning requirements. In this section we discuss some of the issues likely to be experienced during a future AVF eruption, regardless of the specific details of the event that occurs.

Total annual waste generated in Auckland (domestic kerbside, commercial, clean fill, and managed fill) was estimated to be approximately 4 million tonnes for 2016 (Auckland Council 2018). Therefore, in all but a best-case scenario, waste generated from an AVF eruption is likely to put intense stress on the existing waste management resources and facilities in Auckland. Therefore, it is necessary to identify ways in which activities can be scaled up during and following an eruption. As the waste will be heavily mixed, waste sorting facilities will be necessary both onsite and at processing facilities. Therefore, developing a database of waste collection and processing facilities and their relative capacities will be an important aspect of readiness tasks for disaster waste management planning in Auckland. If these facilities are unlikely to be able to cope with the expected quantities of disaster waste, contingency plans should be explored to identify criteria and options for where and how disaster waste can be processed and disposed.

Access to some areas to conduct clean-up will require strict access controls. It is unlikely that it will be safe for workers to enter an evacuated area to begin clean-up whilst an eruption is still in progress. It is likely that there will be substantial waste mixing in areas within a few kilometres of the emergent vent, an area most likely to be under evacuation orders. This is particularly true of areas affected by PDC activity. The dynamic pressure of the PDC can cause failure of roofs and walls, and cause fires. The resultant waste is therefore likely to be a mixture of debris (some fire damaged) and the PDC deposit. Fire damaged material can be hazardous to health of clean-up workers. In addition to building debris, downed powerlines will also be evident in these areas (Deligne et al. 2017b). Thus, it is likely that these areas will require access restrictions not only during eruptive activity, but also for some time following the eruption until health and safety hazards can be managed. Identification of protocols and criteria for re-entry into evacuated areas will be of considerable importance to disaster waste management following an AVF eruption.

To minimise risks to human health and the environment, household hazardous waste (e.g., paint, household chemicals, waste oil, agricultural chemicals, car batteries, and solvents) will require removal before residential dwellings can be demolished (Auckland Council Solid Waste Bylaw 2012, part 1; Auckland Council 2018). In Canterbury New Zealand, over 334 tonnes of household hazardous waste were removed from approximate 8000 homes before they were demolished (~42 kg per house) through a targeted programme as part of the recovery effort from the earthquake sequence (Latham 2016). It is not simple to determine exactly how many houses may be demolished after an AVF eruption, but we can obtain an idea of the potential scale if we assume all DS4 and DS5 houses in the DEVORA scenarios will be demolished and assume the quantity of hazardous waste per house in Auckland is like Canterbury. Under these circumstances, half of the DEVORA scenarios would require more household hazardous waste removal than occurred in Canterbury (Table 6.12). This suggests that a similar household hazardous waste removal project and cross agency approach as conducted in Canterbury will be required following a future AVF eruption.

6.6.3 Additional waste generation mechanisms

The quantification undertaken in this paper considers direct waste generation mechanisms. However, other effects from the eruption (e.g., evacuation, power outages, response activities) are also likely to generate waste. For example, it is possible that power outages could be a long-lasting issue due to an AVF eruption

(Deligne et al. 2017b). This could have consequences for large warehouses storing perishable products, particularly if backup power is disrupted and are located within restricted access areas (e.g., Luther 2008). Therefore, this could require considerable disposal of large quantities of inventory. Scenarios that affect a high number of industrial areas (e.g., Scenario A – Auckland Airport, Scenario B – Ōtāhuhu, Scenario C – Māngere Bridge, Scenario E – Waitematā Port) are most likely to result in these waste streams. Unwanted donations, healthcare waste, and packaging from relief efforts are also a common disaster waste management issue that may require attention (Solis et al. 1995; Ekici et al. 2009; Brown et al. 2011). Damage to some infrastructure systems could also contribute to the disaster waste management requirements (Brown et al. 2011). For example, large scale ingress of tephra into sewer systems may result in an increase in volume of raw sludge within primary treatment tanks at wastewater plants and damage caused to components at wastewater treatment plants has previously led to sewage discharge into rivers (Wilson et al. 2012). Damaged vehicles have also required management following other disasters (Blong and McKee 1995), and the relatively high passenger vehicle ownership rates in New Zealand (617 per 1000: OECD 2019) suggest this is likely to be an issue following a future AVF eruption. Scenario A – Auckland Airport also has the potential for aircraft to be damaged by PDC, ballistics, and tephra if not removed prior to eruption surface breakout.

Table 6.12: Potential household hazardous waste quantity for the DEVORA scenarios

Scenario	Number of DS4 and DS5 houses	Estimate of household hazardous waste (tonnes)
A - Auckland Airport	693	30
B - Ōtāhuhu	12,547	527
C - Māngere Bridge	23,533	988
D - Mt. Eden Suburb	17,987	755
E - Waitematā port	13,299	559
F - Birkenhead	832	35
G - Rangitoto Channel	2,113	89
H - Rangitoto Island	0	0

6.7 CONCLUSIONS

Disaster waste management following volcanic eruptions is an important aspect of disaster response and recovery. Approaches to quantify the potential waste generation are useful as they facilitate planning and help identify future disaster waste management requirements. To date, there has been limited consideration of how disaster waste could be modelled for volcanic events to provide useful insights for contingency planning. In this paper, we developed the first disaster waste modelling framework to quantify disaster waste from volcanic eruptions for use in contingency planning. The framework is based on taking a heuristic approach to identifying the likely waste generated at different states of damage and apply this to a suite of scenarios. The framework developed within this chapter can potentially be used in urban environments around the world exposed to volcanic hazards.

The approach developed in this work was applied to a suite of scenarios for the Auckland Volcanic Field. The outputs from this analysis can be used for contingency planning and indicate considerable complexity associated with trying to clean-up a post-AVF eruption and this will likely be highly contextual to the specific scenario that manifests. However, some high-level conclusions useful to strategic planning about disaster waste management in Auckland can be made. Firstly, AVF eruptions will generate large volumes of highly mixed waste streams that are complex to manage because of sorting, disposal, and health and safety requirements. Thus, this provides some baseline information for planning for the resources required for sorting and disposing this material. Secondly, a stratified management approach may be advantageous where volunteers help clean-up areas affected by minor depositions of tephra, but where specialist personnel and equipment are used to clean-up highly damaged areas. The classification of clean-up zones illustrates how large each of these respective areas are likely to be and the required labour to clean these areas. Thirdly, it is likely that a high degree of uncertainty will be associated with the end of the eruption and when access restrictions can be lifted. Identification of re-entry criteria will be of critical importance to ensure the health and safety of clean-up workers and eventually the wider public.

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Chapter 7: Summary

7.1 THESIS SYNOPSIS

The aim of this thesis was to improve understanding of clean-up and disaster waste management issues after volcanic eruptions. I achieved this by investigating case studies and developing modelling frameworks that can be used for planning purposes. The findings contained within this work help inform DRR measures for volcanoes as they report on the issues that make volcanoes different from other natural hazards for disaster waste clean-up. There were a number of gaps associated with understanding the dynamics of disaster waste management and clean-up of urban areas after volcanic eruptions such as: 1) lack of consolidated or comprehensive literature investigating the link between volcanic activity and disaster waste management, 2) limited post-disaster data collection of disaster waste clean-up related issues, 3) limited development and validation of modelling approaches that are useful for contingency planning purposes. This thesis addresses these gaps by:

1. ***Using international case studies to contextualise disaster waste clean-up and management after volcanic eruptions.***

   I achieved this objective by conducting an analysis of 13 diverse case studies to investigate challenges and planning considerations associated with disaster waste management after volcanic eruptions (Chapter 2). A comprehensive post-eruption impact assessment was also undertaken of the 2015 Calbuco volcanic eruption, Chile (Chapter 3, Chapter 4, and Appendix A). The Calbuco impact assessment was important to achieving this objective because it allowed for key insights into tephra clean-up across four different communities that were affected by the eruption.

2. ***Developing and improving modelling techniques that aid in the planning of post-eruption clean-up requirements***

   For many communities the effects of volcanism are exotic and rarely experienced first-hand. Therefore, it is important to develop modelling approaches that can yield useful and credible information so that plans can be developed in preparation of potential future eruptions. I achieved this objective through testing of an established tephra clean-up modelling approach (Hayes et al. 2017) with real-world information (Chapter 3) and by developing a new modelling approach to assess disaster waste generation and management from a variety of volcanic hazards (Chapter 6):

- First, the 2015 eruption of Calbuco volcano, Chile, was used to test the tephra clean-up model published in Hayes et al. (2017), by using real world data from the Calbuco 2015 eruption (Chapter 3). This exercise demonstrated the challenges associated with accurate forecasting of potential volumes of tephra that would need to be removed and the potential corresponding clean-up operation durations, but that such modelling approaches could yield adequate information for planning purposes.
- The second component was to develop a framework for quantifying and classifying waste produced from a range of volcanic hazards (Chapter 6). A conceptual approach was adopted to estimate the quantity and type of debris generated at different damage states by using information contained within Chapter 2, 3, and 4, as well as taking concepts from disaster waste assessments of other perils. A qualitative method to zone clean-up areas based on the likely clean-up requirements was developed using information from Chapter 2 and an existing framework on tephra clean-up (Hayes et al. 2015).

3. ***Develop a suite of volcanic eruption scenarios for the Auckland Volcanic Field (AVF) that consider a credible range of expected phenomena and can be used to quantify and characterise disaster waste clean-up from AVF eruptions.***

   To be able to test the modelling approaches and obtain useful information for disaster waste clean-up planning in Auckland, New Zealand, it was necessary to develop credible hazard scenarios. I achieved this objective by developing a suite of realistic eruption scenarios for the AVF that consider the temporal evolution of volcanic hazards during an eruption sequence (including unrest). A central component of this was to ensure that stakeholder participation and feedback was incorporated throughout the scenario development process. The eruption scenarios then have the capacity to provide credible, legitimate, and relevant information for a variety of disaster risk reduction activities in the future (including disaster waste management).

The scenarios were then used as a test case for the clean-up and disaster waste management framework developed in objective two (Chapter 6). This analysis provided useful insights into the quantities of debris likely to be generated and the management requirements in different parts of Auckland under different volcanic eruption scenarios.

7.2 RESEARCH AND CONTRIBUTION

The findings in this thesis are a substantial contribution towards volcanic risk assessment and disaster waste management by furthering the conceptual development of disaster waste management after volcanic eruptions and associated body of knowledge of this topic and presenting a new modelling framework to support decision-making for volcanic waste clean-up and management. This topic has had very limited previous attention and so this study makes a substantive contribution to address this knowledge gap. The findings of the thesis contribute to readiness, response, and recovery of urban areas affected by volcanic eruptions by:

- Identifying planning issues associated with disaster waste clean-up after volcanic eruptions (Chapters 2 and 3).
- Demonstrating the utility of an interdisciplinary approach that integrates diverse data and manages diverse stakeholder needs to collaboratively develop a suite of volcanic eruption scenarios. These can be used in a variety of disaster risk reduction activities, including assessing disaster waste generation (Chapter 5). Research outlining applications of such approaches have seldomly been reported for volcanic risk studies, so this represents an important research contribution to the discipline.

- Contributes towards filling critical knowledge gaps in volcanic impact assessment, such as limited reporting on the effectiveness of mitigation actions such as tephra clean-up (Chapter 3) and a limited comprehensive analysis of building damage (Chapter 4).
- Developing modelling approaches that can be used to assess disaster waste management requirements in urban areas affected by volcanism (Chapter 3 and Chapter 6).

7.2.1 Planning for clean-up of urban areas after volcanic eruptions

Planning for disaster waste management is a complex undertaking (Brown et al. 2011). The research in this thesis identified three major reasons for this that differentiate volcanic eruptions from other perils when planning:

1. **Multitude of waste generation mechanisms.**

   It is important to characterise the type and quantity of disaster waste streams that may manifest during a disaster. To do so requires understanding the potential mechanisms that can generate disaster waste. There are many ways that waste can be generated from volcanic eruptions largely due to the different volcanic hazards and their respective waste generation mechanisms (Chapter 2). To plan disaster clean-up after volcanic eruptions will require hazard identification and, in some situations, may necessitate multiple volcanic hazards be assessed to analyse the likely intensity, frequency, and/or magnitude of that hazard. Such assessments can be time consuming and data intensive. There is limited post-eruption damage data available to construct fragility or vulnerability functions (Chapter 4), which must be used in conjunction with hazard assessments to identify damage from a future eruption. Secondly, each of these hazards can interact complexly with one another and the built environment (e.g., cascading hazards). There are few existing models available that account for such interactions. The models that do exist can be specific to a specific volcano and/or be computationally expensive to fully characterise.

2. **Uncertainty associated with volcanic activity.**

   Many of the existing technical guides for disaster waste management work under the assumptions from the earthquake literature, which assume a short duration impact and clean-up can begin almost immediately post-event. However, through analysis of case studies in this thesis I found that this may not be possible for volcanic eruptions (Chapter 2). Identifying how an eruption will progress through an eruption sequence is an area of immense uncertainty (Marzocchi and Bebbington 2012; Bebbington and Jenkins 2019). The uncertainty may also make some existing policies difficult to use. For example, insurance policies sometimes stipulate that after a damaging event, action must be taken to mitigate further building damage. For a hazard such as tephra fall, this would require removal of tephra from a building's roof. However, this might not be possible or advisable if an eruption is continuously erupting or displaying concerning unrest activity.

3. **Variable waste streams and potential for mixing.**

Volcanic eruptions have the potential to produce the same waste streams as any other peril (e.g., construction and demolition, hazardous waste products, vegetative debris, putrescent waste), with the addition of copious amounts of volcanic products (e.g., tephra, lava). The co-location of multiple different waste streams that are likely to be highly mixed requires sorting and careful handling to ensure that appropriate waste treatment actions are undertaken (e.g., appropriate disposal, reuse/recycling, environmental management). Mixed waste streams can occur through many different disaster types (e.g., earthquakes, floods, and tsunami), but volcanic hazards such as PDCs and lahars are likely to make this particularly difficult due to the potential ongoing life safety risks that may exist.

7.2.2 Research findings from scenario development

Developing useful risk information requires interdisciplinarity and the integration of diverse information to develop credible, relevant, and legitimate insights for disaster risk reduction. There can be a tension in risk assessment between workers that prefer fully deterministic and those that prefer fully probabilistic approaches, but, each has an important role to play in disaster risk reduction (Romeo and Prestininzi 2000; McGuire 2001; Bommer 2000; Thompson and Frazier 2014). Finding a balance between fully deterministic and fully probabilistic approaches to assess hazard in the AVF was a key aspect of this thesis so that disaster waste clean-up issues for Auckland could be investigated. The resulting suite of scenarios were useful because they captured a credible range of AVF phenomena (location, volume, duration, eruption style and hazards) and allow for the assessment of disaster waste management requirements under a variety of conditions. Thus, the approach outlined in this thesis is useful for developing a suite of eruption scenarios for volcanism and the exploration of complex planning requirements.

7.2.3 Research findings from disaster waste clean-up modelling

In Chapter 3 and 6 I found that using modelling approaches to assess potential clean-up requirements of volcanic eruptions is a useful method for contingency planning. Previous work has been conducted on modelling clean-up of tephra deposits after volcanic eruptions for loss modelling and contingency planning perspectives (e.g., Johnston et al. 1997; Magill et al. 2006; Hayes et al. 2017; Biass et al. 2017). The work in this thesis has explored tephra clean-up modelling using a real-world case scenario (Chapter 3) to investigate how effective this technique is at producing credible and useful estimates. I found that there is considerable uncertainty associated with modelling outputs, but that modelling approaches produce results that are useful for contingency planning purposes. I also found that using specifically designed and considered tephra clean-up thresholds for urban areas are necessary to obtain realistic model outputs. For example, tephra clean-up in Ensenada was poorly captured using the existing thresholds, possibly due to characteristics of the area such as being a rural farming area that is sparsely populated, and with a relatively high incidence of absentee owners with holiday homes in the area. Therefore, this demonstrates the importance of customising clean-up thresholds based on characteristics of the study area.

Chapter 6 explored how different waste streams could be included within multi-hazard impact assessments for volcanic eruptions. The multi-hazard analysis of waste generation allows for a more thorough analysis of disaster waste management requirements than previously utilised in volcanic impact assessment literature. In this work I demonstrated how this could be used to provide an ‘end of event’ quantification of waste, which is typical of assessments undertaken for other perils (e.g., earthquakes, floods) and is usually a key ingredient for disaster waste management planning (Brown et al. 2011). In addition, I also demonstrated that exploring how waste may accumulate through an eruption sequence is also useful because it provides a more informative picture of how resources may need to be organised in a post-eruption environment, which will be important to consider if the eruption is likely to be long-lasting. Such analyses are critical to provide realistic information relating to the resource requirements for responding and recovering from volcanic eruptions.

Auckland specific findings from the modelling include:

- Large quantities of debris and volcanic products are likely to exceed existing capacity of the Auckland waste management system, requiring disaster specific waste collection, treatment, sorting, reuse/recycling, and disposal systems to be conducted. This will require specific planning that has not yet been conducted in Auckland.
- If phreatomagmatic eruptions and associated hazards manifest during an AVF eruption (occurred in > 80% of previous AVF eruptions), highly mixed waste streams will be generated potentially up to several kilometres from the active vent. These areas are likely to be difficult to clean up due to risks associated with life safety (e.g., proximity to the active vent), human health and safety risks associated with the waste (e.g., partially collapsed buildings, downed powerlines), and the complexities involved with accessing, sorting and treating these waste products (e.g., roads buried by thick volcanic deposits).
- The largest waste type by weight is likely to be the volcanic products, but where these are in greatest accumulations, they are also likely to be highly mixed with damaged building materials. Careful sorting of these products will be necessary before disposal and clean-fill options may not be applicable due to contamination of the volcanic products. This has important implications of the identification of appropriate disposal sites, which earlier work assumed would only contain tephra deposits (Johnston et al. 2001).
- The area of Auckland requiring substantial land remediation is likely to be highly localised, meaning that most of Auckland will be able to be cleaned up following AVF eruptions. However, these areas may require access restrictions for a long period of time until dangerous waste products are removed, and the eruption has been accessed as over.

7.3 BENEFITS AND LIMITATIONS

In this section I discuss the benefits and limitations of the methodological approach undertaken in this thesis.

7.3.1 Case studies and evidence base

Case study research is a useful research tool due to the inherent flexibility of the approach. This was particularly useful for developing new knowledge relating disaster waste management and volcanic hazards, which was a major knowledge gap in disaster research. Specifically, there has been limited detailed reporting of case studies from a disaster waste clean-up perspective. Therefore, the case studies in this thesis are limited to a relatively small selection of relatively high-profile case studies when compared to the diversity of volcanic hazards and societies affected by them. The consequence is that there may be issues associated with disaster waste management and volcanic hazards that I have not identified in this thesis.

7.3.2 Scenario development

There were numerous benefits obtained from the scenario development conducted in Chapter 5. It can be time consuming and challenging to fully characterise the uncertainty required for fully probabilistic volcanic hazard modelling. This is particularly challenging in a complex multi-volcanic hazard environment like Auckland, where location and eruption styles can vary substantially in space and there is no historical or measured information to rely upon. Therefore, the scenario development process was a useful middle ground between a fully deterministic and fully probabilistic approaches as it facilitated the development of useful information that could be used for ongoing disaster risk research in the immediate future. This means that multiple research strands can continue to advance, whist better understanding of AVF hazards is undertaken to produce a fully probabilistic hazard assessment.

Scenario development provided a useful mechanism to grow the links between knowledge producers and knowledge users. Volcanologists, disaster risk researchers, policy advisors, and emergency managers were all involved in the development of the

DEVORA Scenarios. The role of volcanologists was to ensure that the resulting scenarios were scientifically credible and that the underpinning information was being correctly applied, whilst disaster risk researchers, policy advisors and emergency managers ensured the scenarios remained relevant by overseeing and reviewing that the outputs were in an appropriate format for use in disaster risk reduction activities (e.g., impact/damage modelling, desktop simulation exercises, public communication).

As the scenarios were intended to capture all aspects of an eruption, from identification of precursory unrest activity through to surface breakout and the manifestation of multiple different volcanic hazards, the scenario development process was also useful for identifying several major knowledge gaps relating to AVF volcanism. For example, lava flow and PDC hazards represent major sources of potential damage and loss from a future AVF eruption, but the scenario development process highlighted that existing ability to model these is quite limited for the AVF. Both are now currently under investigation in parallel research projects (EQC 2018; Tsang et al. in prep). Additionally, gas dispersion is also an acknowledged hazard but relies upon having accurate gas flux information and appropriate modelling of gas dispersion within the atmosphere. This is also the subject of ongoing research (Smid et al. 2018).

A limitation of the scenario development was that hazard models in volcanology typically only consider a single specific hazard process (e.g., tephra fall, lava flow), sometimes specifically customised for a specific volcano. However, volcanic eruptions are complex events that involve many interacting hazardous processes, which makes taking a holistic approach like the one I used in this thesis difficult. How model outputs might influence one another (e.g., development of a maar crater or scoria cone and influence on subsequent lava flows) were considered, but were highly reliant on expert judgement, which placed limits on the transparency and independent repeatability of the approach.

The interdisciplinary approach was time consuming as it required regular reviews, workshops, and meetings with a variety of stakeholders with differing and sometimes conflicting views on the outputs that should be produced. Time commitments of this approach may make it difficult to transfer to some other areas.

Locations where specialists are lacking and/or relationships between stakeholders are not well developed may particularly find this challenging.

An AVF eruption could last more than 12 months, but no such scenario was considered in the DEVORA Scenarios. This is because eruptions have the potential to substantially alter local environmental conditions, which would require highly speculative assumptions such as changes to hydrology. Thus, the results presented in this thesis must be viewed within the context that a long-lasting eruption has not been considered.

7.3.3 Disaster waste clean-up modelling

Chapter 3 demonstrated that geospatial modelling of tephra clean-up can provide credible and useful estimates of the volume and duration of clean-up operations. Useful information generated from this work included estimates of the volume of tephra requiring removal and the potential duration of clean-up activities, which is fundamental information for identifying resource requirements to restore a community to normality after a tephra fall event. However, customisation of tephra clean-up thresholds, number and type of trucks, and location to disposal sites are necessary for this approach to be replicated in other areas. However, this information is not always available and maybe challenging to obtain.

Chapter 6 demonstrated that potential waste types and quantities from volcanic eruptions can be derived from modelling approaches. There is limited information specific to New Zealand buildings that indicates the material stock contained within different building classes like those contained in the RiskScape building dataset. This required broad rules-of-thumb to be adopted, which reduces the reliability of the estimates. Although the estimates appear credible when compared to a range of disasters, a lack of reporting on building waste generation from volcanic eruptions means it is not possible to compare or evaluate the accuracy of this approach with international examples.

Both tephra modelling of Chapter 3 and the more comprehensive disaster waste characterisation of Chapter 6 require adequate asset inventories. Data requirements for tephra clean-up modelling include: roads (type and width), impervious surfaces (e.g., pavement), building footprints, and land use/land cover. These data have previously been difficult to obtain with the necessary accuracy and detail, but with the increasing development of volunteer driven geospatial information sources such as Open Street Map and remote sensing approaches, these are becoming more accessible for many urban areas exposed to tephra fall. To conduct the modelling in Chapter 6 requires high quality and detailed building datasets, which are rare globally. They also require adequate approaches to link building asset classes to the material stock contained within them (e.g., quantity of concrete). Without this information broad measures using rules-of-thumb must be applied, which can still provide useful information for planning purposes, but requires uncertainty to be acknowledged and transparently communicated.

7.4 FUTURE RESEARCH

In this section I discuss areas of future research that are required to build upon the work contained in this thesis.

7.4.1 Field data collection

Field collected post-disaster data is one of the most important pieces of information for disaster risk work because it allows researchers to develop and test risk information products (e.g., fragility functions and hazard models) from real-world events. This information facilitates development of lessons learned, conceptual and empirical models (e.g., Chapter 4), and validation/testing of some of these models (e.g., Chapter 3).

I demonstrated in Chapter 2 that many different waste streams can be generated from volcanic hazards (e.g., construction and demolition, electronics, perishable), yet there is very little detailed documentation of the disaster waste streams, quantities, and management requirements following volcanic eruptions. The disparate and inconsistent reporting on the waste generated following any disaster (but particularly volcanic eruptions) to date makes the process of empirically quantifying and characterising solid waste generation (e.g., construction and demolition debris) challenging. Case study reports that investigate across the spectrum of disaster waste management issues would be of considerable value to investigating some of the gaps in this analysis. Attention towards clean-up and recovery activities associated with proximal areas where multiple eruptive hazards may interact is a clear research area requiring attention. Thus, I highly recommend future forensic disaster studies (e.g., Wantim et al. 2018) and post-eruption impact assessments (e.g., Blake et al. 2015) consider these issues in future as a priority.

The study of building damage from the Calbuco eruption (Chapter 4) demonstrated the challenging data quality issues that must be managed when relying on secondary data sources, often necessary when assessing volcanic impacts. Part of the problem is that there is a disconnect between field-based volcanological studies and the use of that information in deriving impact-based functions (e.g., fragility or vulnerability functions). Interdisciplinary field-based teams are crucial for reducing this disconnect so that appropriate data can be gathered to provide better engineering insights. However, this is often not possible due to logistical and/or health and safety concerns. Therefore, I suggest that robust assessment and documentation practices are developed, and consistent use of terminology are particularly important to reduce the potential for errors. Standardisation of data collection processes would be of use to maintain minimum standard of data quality. Data quantity could be improved by making any such standards and underlying data openly accessible in some form (e.g., publication in open access data repositories) so they can be appropriately scrutinised. Investigations into the appropriate methods of standardising this data collection and evaluating data quality will be an important aspect of future proofing this important information.

7.4.2 Multi-hazards and cascading impacts

There are several cities around the world that face similar challenges with volcanic risk management like Auckland. Thus, it is of importance to gain more knowledge regarding how volcanic hazards interact with one another and the urban environment, and how these processes can be incorporated into modelling frameworks. This was listed as an acknowledged priority research area by the volcanic risk assessment community at the 1st IAVCEI/GVM workshop "From Volcanic Hazard to Risk Assessment" (Bonadonna et al. 2018). One of the fundamental issues is that volcanic hazard models are often designed for specific hazards and commonly for a specific volcano. Therefore, knowledge and advice must be communicated towards how these models or new models can be integrated for multi-hazard modelling in volcanology. Additionally, spatio-temporal and dynamic hazard and vulnerability models are needed to greatly enhance scientists' ability to assess how impacts can evolve through eruption sequences.

7.4.3 Improving disaster waste clean-up modelling capability

The approach developed in this thesis for modelling disaster waste clean-up requirements relies upon up-to-date and high-quality asset databases. High quality databases are rare across the world (Simpson et al. 2014). Thus, cost-effective development of asset databases requires consideration so that this information can be obtained on a large enough scale for use in disaster waste assessments. Advances in artificial intelligence and machine learning approaches using Earth observation techniques appears to be a particularly promising research avenue for this purpose (Geiß et al. 2015; Jochem et al. 2018; Yuan et al. 2018).

As a next step towards greater understanding of disaster waste clean-up, I suggest that gathering data and analysing the spatial and temporal dynamics of clean-up operations will yield useful information on priorities and demand for resources through a clean-up response. Such an analysis could be conducted using Earth observation techniques and tracking waste removal at city block scale through regular satellite images. Alternatively, or in combination, on-the-ground assessments could be undertaken by developing a set of clean-up states (similar approach to damage states) that described the required clean-up activities and through repeat visits to a set of indicator sites track the change in clean-up states through time.

Asset data are currently not well set up for assessing disaster waste requirements in New Zealand. A weakness with existing data is the lack of a high-quality material stock analysis to evaluate potential waste streams generated from disasters, requiring a heavy reliance on rules-of-thumb (Chapter 6). The multiple waste generation mechanisms from multiple volcanic hazards makes this a particularly difficult endeavour because different volcanic hazards can affect buildings in different ways. I suggest that a national material stock analysis is conducted so that modelling approaches can be standardised within the New Zealand Disaster Waste Management Planning Tool. The RiskScape asset database is the most widely used building dataset for disaster risk analysis in New Zealand so it would be logical that material stock analysis is conducted using the asset classes within. This could be conducted as part of a wider survey for parameters for all RiskScape.

The benefits of having detailed material stock analysis data go beyond clean-up planning considerations. Material stock analysis can be used to identify the flow of different building materials in a system and determine potential demand for resources during post-disaster recovery and renewal efforts (e.g., Hashimoto et al. 2007), which helps identify industries and workforce requirements to meet the needs of urban recovery (e.g., Chang et al. 2010). This information can also identify the environmental consequences (e.g., increased greenhouse gas emissions from rebuilding) and impacts on global obligations (e.g., Paris Agreement: United Nations 2015) of undertaking different rebuilding approaches (Pan et al. 2013). Such considerations may become important if the proposed Climate Change Response (Zero Carbon) Amendment Bill 2019 are passed into legislation due to the requirements to set emissions budgets under the proposed bill (see clause 8).

7.4.4 Waste minimisation

Finding ways to minimise waste through recycling and reuse of the waste products is useful in disaster waste management to reduce required landfill space, incineration of waste, and the demand for raw materials, and potentially increase post-disaster job creation (Asari et al. 2013; Brown and Milke 2016). There have been studies which have investigated the technical and logistical requirements of recycling waste after disasters (e.g., Fetter and Rakes 2012; Asari et al. 2013; Brown and Milke 2016; Tabata et al. 2019). Studies have also investigated the use of volcanic deposits for a variety of uses (e.g., Hossain 2003; Hossain and Lachemi 2007; Tchakoute et al. 2013; Pappalardo et al. 2017). However, these studies use pristine products and focus on the technical aspects of reuse. There is limited research investigating the use of volcanic products that have been collected from urban areas as part of clean-up activities, particularly if the product is contaminated with other waste products (e.g., Contrafatto 2017). The design of rapid assessment frameworks so that reuse potential can be identified using a few easily measurable/observable indicators (e.g., grainsize, chemistry, mineralogy) would be of considerable utility as it would allow waste managers to quickly develop processes to separate potentially reusable products (for more detailed characterisation) from those that have no use.

7.4.5 Disaster waste management from volcanic eruptions in low-income nations

Many of the findings in this are focussed on high-income nations and may not be transferable to low-income or low-middle-income nations. Low-income nations may not have the adequate waste management systems during non-disaster times, without even considering systems that can be utilised during disasters (Henry et al. 2006; Karunasena et al. 2009; Brown et al. 2011). The United Nations (UN) Joint Environmental Unit (JEU) have prepared draft guidelines for disaster waste management in developing nations, but despite covering specifics of earthquakes, flooding, tsunami, hurricanes/typhoons, and conflicts, they do not feature any information relating to volcanism (JEU 2010). As there are many low-income or low-middle-income nations that are also exposed to volcanic hazards (Brown et al. 2015) focussed consideration of the unique challenges and potential mitigation options for low-income countries is necessary.

The approach used in this thesis to assess disaster waste clean-up may present some challenges if being undertaken in low-middle-income nations. For example, the modelling undertaken in chapter 6 has substantial data requirements, such as highly detailed building and road inventory data and vulnerability models. This information may not be available to the same quality and quantity in some low-middle-income nations (Simpson et al. 2014). Chapter 3 demonstrated how open-source data sources can be used (e.g. OpenStreet Map) for societal elements at risk, but that careful consideration of the data quality and potential limitations is required. Satellite data is freely available for many areas of the world and can be used to either manually (e.g. Chapter 3) or automatically (e.g. Grinias et al. 2016) obtain. Global exposure datasets are also available, and with downscaling can be used to produce national level databases (e.g. De Bono and Mora 2014; Gunasekera et al. 2015). At a practical level, this would require additional steps to the approach used within this thesis to obtain, validate, and ground-truth this information. However, this still requires access to the technology and skills to produce it. Thus, at a fundamental level, it is necessary to continue to build capacity within low-middle-income nations to undertake disaster risk assessments.

To reduce disaster impacts, countries need to invest in disaster risk reduction (UNISDR 2015). However, it has been established that low income countries are faced with a number of challenges for implementing Disaster Risk Reduction strategies (Kenny 2012). Undertaking many of the required elements of this work, such as detailed hazard and risk assessment, strong and stable institutions of state, and integrated disaster risk management planning may be difficult to establish and sustain in such contexts (UNISDR 2015). This is in part due to limited financial, technical, and expert resources available in these areas (Kenny 2012). Consequently, disaster waste planning is often lacking as it has not been mainstreamed in disaster risk management (Karunasena et al. 2009; Brown et al. 2011). Identifying capacity gaps (e.g. legislation and regulations, scientific expertise, organisational structures, trained staff) is a critical task for low-income countries to prioritise resources for improved disaster waste management (Poulsen 2007; Karunasena et al. 2009)

7.5 MUSINGS ON THE FUTURE OF DISASTER WASTE MANAGEMENT

With increasing population growth and urban development, the rate of waste generation is rapidly increasing, whilst the available land to dispose of it is rapidly decreasing, making waste management is one of the great challenges of modern times. (Kaza et al. 2018). Many major urban centres have waste management policies, where they estimate the expected amount of waste generated over the coming decades to identify potential needs over the long term. Currently, the generation of disaster waste is not included within these waste management policies and is instead treated as a special case to be dealt with if the situation ever arises. As demonstrated in this thesis and following numerous other recent disasters, the quantity of waste produced by disasters can be many decades worth of business-as-usual municipal waste. Embedding disaster waste generation within long-term waste management policy documents has the potential to place increased prioritisation towards managing disaster waste. For example, comprehensive analysis of the potential waste generation from all hazards to an urban area will allow for an estimate of the expected waste quantity to be generated over the planning timeframe. However, to do so requires more accurate forecasting tools of both disasters and likely waste generation through enhanced analysis of dynamic risk (e.g., evolving hazardscape, exposure, and vulnerability through space and time). These areas of research are in their infancy but are likely to receive heightened attention over the coming decades.

There is increasing attention on the development of smart waste management systems in the search for enhanced solid waste management system efficiency (Esmaeilian et al. 2018). Although in their infancy, these systems are typically sensor-based technologies that are used within rubbish bins to quantify and characterise waste and use the derived data to monitor and facilitate scheduling and routing of waste collection and disposal automatically in real-time (Esmaeilian et al. 2018). These systems are designed assuming business as usual municipal waste management systems, but if cities are to consider transitioning towards these approaches it will be necessary to evaluate how disasters may affect smart waste management systems and whether they are scalable to work under disaster conditions.

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Appendices

Appendix A: Impacts of the 2015 eruption of Calbuco volcano on Chilean infrastructure, utilities, agriculture, and health

Hayes, J.L.; Deligne, N.I.; Bertin, L.; Calderon, R.; Wardman, J.B.; Wilson, T.M.; Leonard, G.S.; Stewart, C.; Wallace, K.L.; Baxter, P.J. 2019 Impacts of the 2015 eruption of Calbuco volcano on Chilean infrastructure, utilities, agriculture, and health. Lower Hutt, N.Z.: GNS Science. GNS Science report 2019/04. 102 p.; doi: 10.21420/02YC-VX66

Appendix B: Ethics applications and consent forms used for Calbuco impact assessment

Human Ethics Committee – Staff Application

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

For Office Use Only –	**HEC Reference:**	
Date Received:	**Reviewers:**	
Date Approved:	**Approved:**	**(HEC Chair)**

Please remember that your audience for this application form, as well as all forms for participants, will include community members and scholars from outside your discipline and therefore must be written in everyday language.
This form should be completed after reading the *Research Involving Human Participants* issued by the Human Ethics Committee available at http://www.canterbury.ac.nz/humanethics
If this is research towards a degree, eg PhD, please use the Student Application Form.

Will another ethics committee review this application?

- If a New Zealand Health and Disability Ethics Committee (HDEC) is reviewing your project, please send your HDEC application to us with this coversheet, and then the approval. You do not need to fill out the full University of Canterbury application form.
- If you have ethics approval from another institutional ethics committee (eg another New Zealand or Overseas University ethics committee) and you will conduct your research in the country of that ethics committee, please send this coversheet only with that application and the later approval letter, and an explanatory email. You do not, initially, need to fill out the full University of Canterbury application form.

Please ***Bold*** your answers

Project Title: **Assessing the vulnerability of critical infrastructure and primary industries to volcanic ash fall hazards in Chile and Argentina**

Applicant: **Dr Thomas Wilson**

University Programme/Department: **Department of Geological Sciences, University of Canterbury**

Primary Phone: **+64 21 434596**

Email: **thomas.wilson@canterbury.ac.nz**

Additional Team members

Researcher's Name: **Mr. Josh Hayes**

Department and University: **Department of Geological Sciences, University of Canterbury**

Email: **josh.hayes@pg.canterbury.ac.nz**

Contact details: **+64 21 2095248**

Researcher's Name: **Dr. Natalia Deligne**

Department and University: **GNS Science**

Email: **n.deligne@gns.cri.nz**

Researcher's Name: **Dr. Graham Leonard**

Department and University: **GNS Science**

Email:**g.leonard@gns.cri.nz**

Researcher's Name: **Dr. Carol Stewart**

Department and University: **Joint Centre for Disaster Research, GNS Science / Massey University**

Email: **c.stewart1@massey.ac.nz**

Researcher's Name: **Mr. Daniel Blake**

Department and University: **Department of Geological Sciences, University of Canterbury**

Email: **daniel.blake@pg.canterbury.ac.nz**

Researcher's Name: Mr. **George Williams**

Department and University: **Department of Geological Sciences, University of Canterbury**

Email: **georgette.williams@pg.canterbury.ac.nz**

Researcher's Name: **Mr. Tyler Barton**

Department and University: **Department of Geological Sciences, University of Canterbury**

Email: **tyler.barton@pg.canterbury.ac.nz**

Researcher's Name: **Dr. Gustavo Villarosa**

Department and University: **National University of Comahue, Bariloche, Argentina**

Email: **gvillarosa@gmail.com**

Researcher's Name: **Dr. Valeria Outes**

Department and University: **National University of Comahue, Bariloche, Argentina**

Email: **valeria.outes@gmail.com**

RESEARCHER'S SIGNATURE

I *Thomas Wilson* have considered the various ethical issues involved in this research and I will conduct this research within the bounds of any approval given by the Human Ethics Committee of the University of Canterbury.

Signed: ____Thomas Wilson_______________________________ Dated: 25 October 2016

LOW RISK PROCESS SIGNATURE

The low risk review process for staff differs from a full application only in that it is examined by two committee members and the Chair of the Human Ethics Committee. As a result it may be possible to reply to the applicant in 7 days.

Please explain why the research is low risk research low risk, noting the information overleaf
If no explanation is provided, the application will be considered a full application.

The HEC relevant objective of the activity is to interview critical infrastructure and primary industry professionals whose role is to manage the risk and any impacts from volcanic hazards. We are interested in their experiences, impacts sustained (if any), and what mitigation measure they undertook (if any).

There will be two types of interview conducted:

a) **Technical interviews (semi-structured) with infrastructure, agriculture or emergency management specialists about their professional role and experience during the eruption crisis. These interviews do not ask questions about social impacts, other than in general terms e.g. the issues the loss of infrastructure service may have on the general population.**
b) **General interviews (semi-structured) with farmers and property owners about their experiences in managing volcanic hazard impacts. Typically, these are focused on physical impacts, such as cleaning ash from properties or rehabilitating soils.**

However, sometimes the conversations stray into social impacts. We deliberately do not ask about psychological impacts. If the interviewee mentions these, we politely and respectfully shift the conversation away from these topics. This is also undertaken if the interviewee is showing any sign they are uncomfortable with the interview. There is a small potential risk that these topics may cause some distress. We attempt to mitigate this risk primarily by keeping topics within the individual's professional domain. We also spend time to carefully identify and select potential interviewees and use established ethical practises. We only use experienced or local translators, who are well versed with the local context and identifying emerging signs of distress. Drs Wilson, Leonard and Stewart each have over 10 years' experience with undertaking semi-structured interviews on the impacts of natural hazard disasters, both internationally (with use of translators) and in New Zealand.

We are very conscious of ensuring we respect and try to understand the local context, both long and short term. We will be actively collaborating with Dr Gustavo Villarosa and Dr Valeria Outes from the National University of Comahue, Bariloche, Argentina. Both are active on local natural hazard risk management committees, and Dr Villarosa is a member of the Argentine national natural hazard risk committee. We have a long-standing research

relationship with them (8 years) which has included work in Chile and Argentina, and broader international efforts on volcanic risk reduction (such as the IAVCEI Cities and Volcanoes Commission). We also have approval and agreement from the Chilean Geological Survey, SERNAGEOMIN (the equivalent of GNS Science), with Dr Hugo Moreno (Head of the Southern Andean Volcano Observatory) agreeing to work with us to ensure the trip contributes to Chilean volcanic risk reduction activities and will join us for some time in the field. By way of further context, this will be the fourth such volcanic impact assessment trip that Dr Wilson has led to Chile and Argentina, along with Drs. Stewart and Leonard. So we have a fairly good understanding of the study area and how to manage risks to the researcher.

We are visiting impacted areas over 12 months since the last ash fall event (2015 Calbuco eruption) – with other locations 5 or 8 years since the major eruptions (2011 Cordón-Caulle and 2008 Chaitén eruptions) respectively. Most of the acute impacts have since passed, so interviewees would be reflecting on their experience, rather than how they are currently coping.

The research does not involve any methods which may:

- **be invasive physical procedures or incur potential for physical harm;**
- **involve Tangata Whenua;**
- **undertake cross cultural research;**
- **investigate illegal behaviour(s);**
- **deal with invasion of privacy;**
- **collect information that might be disadvantageous to the participant,**
- **use information already collected that is not in the public arena which might be disadvantageous to the participant;**
- **use information already collected which was collected under agreement of confidentiality;**
- **involve participants who are unable to give informed consent;**
- **involve a conflict of interest e.g. the researcher is also the lecturer, teacher, treatment-provider, colleague or employer of the research participants, or there is any other power relationship between the researcher and the research participants;**
- **involve deception, involve audio or visual recording without consent; or**
- **withhold benefits from "control" groups or involve inducements.**

Signed (Primary Researcher) ___________________________________ Dated:

SUBMISSION INSTRUCTIONS

Please submit ONE electronic file containing all the necessary documents in a PDF format and ONE fully signed hard copy. Exceptions may be made, but must be discussed first with the HEC Secretary. Processing of HEC applications is unable to begin until a hard copy of the application has been received by the Ethics Office.

Electronic copies should be emailed to human-ethics@canterbury.ac.nz. Hard copies should be sent to the Secretary, Human Ethics Committee (Level 5, Matariki South).

Low Risk application information:

No research can be counted as low risk if it involves:

(i) invasive physical procedures or potential for physical harm
(ii) procedures which might cause mental/emotional stress or distress, moral or cultural offence
(iii) personal or sensitive issues
(iv) vulnerable groups
(v) Tangata Whenua (if in doubt please see the comments under question 12 on the application form)
(vi) cross cultural research
(vii) investigation of illegal behaviour(s)
(viii) invasion of privacy
(ix) collection of information that might be disadvantageous to the participant
(x) use of information already collected that is not in the public arena which might be disadvantageous to the participant
(xi) use of information already collected which was collected under agreement of confidentiality
(xii) participants who are unable to give informed consent
(xiii) conflict of interest e.g. the researcher is also the lecturer, teacher, treatment-provider, colleague or employer of the research participants, or there is any other power relationship between the researcher and the research participants.
(xiv) deception
(xv) audio or visual recording without consent
(xvi) withholding benefits from "control" groups
(xvii) inducements
(xviii) risks to the researcher

This list is not definitive but is intended to sensitise the researcher to the types of issues to be considered. Low risk research would involve the same risk as might be encountered in normal daily life.

This form should be completed after reading the *Human Ethics Policy* issued by the Human Ethics Committee available at http://www.canterbury.ac.nz/humanethics

DESCRIPTION OF THE PROJECT

1. What does the project seek to do?

A recent volcanic eruption of Calbuco Volcano, Chile has highlighted the vulnerability of agriculture and critical infrastructure. Ash falls (up to 20 cm) in these regions primarily caused disruption to essential infrastructure. This project proposes a field trip to Chile and Argentina to research the adverse impacts from this eruption to key infrastructure facilities. Trip objectives include collaboration with local volcanic hazard research centres to gain local insight into the infrastructure facilities and networks most vulnerable to volcanic ash fall hazards (as experienced in recent months), and assessment of the physical damage and loss of functionality of assets at each facility/network (i.e. power generation, water treatment plants, hospitals, clinics, etc.). We also intend to look at how ash fall impacts agricultural productivity and how well emergency management plans meet the needs of the facility and the community during a volcanic crisis. The information gathered will be used to consider what lessons New Zealand can adopt to managing the impacts from volcanic eruptions.

Our local collaborator, Dr. Gustavo Villarosa (Universidad Nacional del Comahue, Bariloche, Argentina) is a volcanologist of good local standing. He contributes significantly to local Civil Defence initiatives to raise awareness of volcanic hazards and mitigate their consequences. We have collaborated together since 2009 when we undertook field work in the same area following the 2008 eruption of Chaitén volcano (Chile) and again in 2012 following the eruption of Cordón-Caulle. We also have approval and agreement from the Chilean Geological Survey, SERNAGEOMIN (the equivalent of GNS Science), with Dr Hugo Moreno (Head of the Southern Andean Volcano Observatory) agreeing to work with us to ensure the trip contributes to Chilean volcanic risk reduction activities and will join us for some time in the field.

2. What is the research question or hypothesis of this project?

How did the 2015 Calbuco eruption affect infrastructure and agriculture in Chile and Argentina?

3. Describe how this project arose ie, please explain the academic area or issue etc which generated the question(s) to be examined – this is to allow lay members of the committee some context for the research.

The impacts of volcanic eruptions are generally much less well understood compared to other natural hazards, such as earthquakes and floods. The New Zealand Volcanic Impact Research Group (co-led by UC and GNS Science) has undertaken overseas volcanic impact assessment trips to gather information on the impacts and management lessons since the late 1990's (following critical knowledge gaps following the 1995-96 Ruapehu eruption). The data from these trips has been used to inform volcanic risk management activities in New Zealand and internationally, with the most publically visible resource being the USGS/GNS Ash Impacts Website – a global resource mostly based on the volcanic impact assessment trip programme (https://volcanoes.usgs.gov/volcanic_ash/). We attempt to partner with local organisations on each trip, to share learnings and build local capacity.

Since 2008 we have undertaken a series of impact assessment trips studying the impacts of large silicic eruptions which have impacted Chile and Argentina, in collaboration with Chilean and Argentinean colleagues. New Zealand has very similar volcanoes which could erupt similar compositional volcanic products, but we have not experienced this during human occupation in New Zealand and therefore have little direct experience of managing such eruptions. This makes learning from overseas eruptions valuable for New Zealand and for other countries around the world (we have presented findings from this research to Japanese, Italian and South Korean governments).

4. How will you go about answering the research question?

We study the physical deposits of ash, any observable physical damage, and (crucially) interview infrastructure and primary industry managers/engineers/farmers about their experiences, impacts sustained (if any), and what mitigation measures they undertook (if any).

There will be two types of interview conducted:

a) **Technical interviews (semi-structured) with infrastructure, agriculture or emergency management specialists about their professional role and experience during the eruption crisis. These interviews do not ask questions about social impacts, other than in general terms e.g. the issues the loss of infrastructure service may have on the general population.**
b) **General interviews (semi-structured) with farmers and property owners about their experiences in managing volcanic hazard impacts. Typically these are focused on physical impacts, such as cleaning ash from properties or rehabilitating soils. However, sometimes the conversations stray into social impacts. We deliberately do not ask about psychological impacts. If the interviewee mentions these, we politely and respectfully shift the conversation away from these topics. This is also undertaken if the interviewee is showing any sign they are uncomfortable with the interview.**

INFORMATION ABOUT THE PARTICIPANTS

5. Who are the participants and why have they been chosen to be asked to participate?

Emergency management, infrastructure specialists and farmers in the areas may be contacted if time allows and their workload permits.

Participants will be interviewed about what impacts ashfall has on infrastructure or primary industry operations and what mitigation measures have been developed to reduce impacts.

The style of the interview will be participant-led and interviewees will be treated respectfully and with sensitivity to the individual's needs (i.e. age, gender, ethnicity, culture, religion, disability or social class).

Language may be a barrier to communication in some areas. We have a number of Spanish speaking members on our team to assist with this concern, who are either local to Chile/Argentina or have lived (>1 year) in Latin America. The translators are aware that participants have the right to privacy and confidentiality and will be expected to maintain this confidentiality. A consent form will be signed by our translators to ensure that he

maintains complete confidentiality for all interview participants.

We will be working closely with local collaborators who are native Spanish speakers in addition to having two fluent Spanish speakers from our New Zealand based team.

Transcript notes are mostly taken using notebooks or laptops – which are then written up into a comprehensive transcript later (usually by verifying between interviewers (if more than one) and translator) -- they are then emailed to the participant for checking if requested.

6. How many participants will be involved (of each category where relevant)? Please include statistical justification where necessary. **We expect to interview between 20 and 30 participants - depending on availability**

7. What selection criteria and/or exclusion criteria will you use? ie, randomly, by age, gender, ethnic origin, other – please give details. What plans do you have if the recruitment phase is too successful, or does not recruit enough participants? **N/A**

8. Describe how potential participants will be identified and recruited?

They will be recommended by our Chilean and Argentinean collaborators while additional participants may be recruited as a result of suggestions from prior interviews/interaction with locals and other facility employees.

9. Does the project involve recruitment through advertising? **NO** (delete inapplicable) If yes, please attach a copy of all variations of this advertising (including e-advertising, eg, Facebook) and discuss any permissions that you have or might need to seek (eg, from organisers of social media/blog/comments pages).

10. How much time are participants asked to contribute to the research? **30-60 minutes**

11. Is any form of inducement to be offered? **NO** (delete inapplicable) If yes, please justify, and include the funding source for the inducements.

12. How will the participants be treated? Describe in practical terms how the participants will be treated, what tasks they will be asked to perform, etc. Indicate how much time is likely to be involved in carrying out the various tasks.

Interviewees will be invited (by phone or email) to participate in an interview. If they do agree, a time and place is arranged. A consent form and information sheet is provided to the participant ahead of the interview (typically by email) and at the beginning of the interview (in hard copy). It is clarified if the participants would be happy to be named in subsequent research publications or prefer to remain anonymous. If they agree to continue, then one of the research team will lead them through questions (often via a translator) about their experience of the ashfall event, what impacts occurred and how they were managed (see

attached question sheet) with another team member writing up their responses. At the completion of the interview, interviewees are invited to review the notes taken by the research team, generally emailed to the participant so they may do so at their leisure.

13. Will forms for participants need to be translated? **YES - Spanish**

14. Will the project require engagement and consultation with iwi Māori? **NO** (delete inapplicable) *If the answer is yes to any of the questions below, please contact the research consultant Maori. The consultant will be able to help you assess whether you need to seek consultation and engagement with iwi Māori through the Ngāi Tahu Consultation and Engagement Group. The consultant will facilitate the engagement process, and provide cultural advice and support. Contact details for the research consultant and other important information and advice regarding engaging with Māori are available at* http://www.research.canterbury.ac.nz/maoriresearch/
    - Will the design, implementation or outcomes of the project have implications for iwi Māori?
    - Will there be significant Māori content, use of culturally sensitive material or knowledge?
    - Will the research require access to Māori sites, or sampling of flora/fauna?
    - Will there be Māori participants or subjects?
    - Will the ethnicity of participants be recorded and likely to result in different treatment for Māori participants during the study or result in statements specifically about Māori in the results?

OTHER PARTIES WITH AN INTEREST IN THE RESEARCH

15. Does the project require permission of an organisation, other people, to access participants or information? **NO – however as a courtesy we ask consent from Chilean and Argentine Emergency Management and local science groups to undertake the work – typically with them as collaborators. We would also typically contact the local Mayor to ask their consent to undertake studies within their communities – which works well in the small, rural communities we tend to operate in and is consistent with local custom. This has built trust and good-will over the past 8 years.**

16. Will the project require Community consultation? **NO**

17. Is the project funded externally? **YES. It is funded by the Natural Hazard Research Platform (GNS Science/MBIE) and GNS Science. There are no conflicts of interest we are aware of.** (delete inapplicable) If yes, please provide details and discuss any conflict of interest issues that may arise.

18. Is the project commissioned by or carried out on behalf of an external organisation(s)? **NO** (delete inapplicable) If yes, please identify the organisation(s) and any Intellectual Property agreements. This includes ownership of data, results and publications.

19. Is the project to be part of the CEISMIC digital archive? **NO** If so, please ensure all participants are made aware of this, and have filled in the UC CEISMIC Quake Studies consent form. See www.ceismic.org.nz.

DATA COLLECTION

20. Does the project involve a questionnaire? **YES** (delete inapplicable) If yes, please include a copy. The HEC does not normally approve a project which involves a questionnaire without seeing the questionnaire, although it may preview applications in some cases where the production of the questionnaire is delayed for good reason. If there is a questionnaire please answer the following questions:

(a) Explain how and why the questionnaire(s) will be anonymous or confidential (Anonymous: you could ***not*** conceivably know who completed it; Confidential: not anonymous, but you will not reveal the identity of the participants to anybody outside the research team)

In any subsequent publications based on interview data, will at no point mention names. Participants will all be referred to as, for example, a 'facility worker' or 'local farmer' and their specific occupation will not be revealed. We will ask for consent to use company names when interviewing facility staff while anonymity will be given to individuals. Participants' name, workplace address and occupation will be recorded but this information will not be disclosed to anyone outside of my research team.

(b) Explain how the questionnaire will be distributed and collected.

The questionnaire will be delivered in person via interviews with participants.

21. Does the project involve a structured or semi-structured interview? **YES** (delete inapplicable) If yes, please list the topics or the specific questions to be covered.

See accompanying documents

22. Does the project involve an unstructured interview? **YES** (delete inapplicable) If yes, please list the topics to be covered.

See accompanying documents

23. Does the project involve focus groups? **NO** (delete inapplicable) If yes, please include a copy of the confidentiality agreement all participants will sign or explain the way that you will protect the confidentiality of participants.

24. Does the project involve recording of Audio, Video or Images? **NO** (delete inapplicable) If yes, please explain the purpose and describe the recording. Please ensure information sheets fully inform participants of the extent and nature of the recording, and explain the legal and ethical issues of ownership of these recordings and how you have resolved them.

25. Will participants will be given the opportunity to check the transcript and/or notes of their interview/focus group? **YES** (delete inapplicable) It is normal practice to give participants the opportunity to review their transcription. If this is not to be the case, please explain why you believe it is not necessary. Participants must be informed of interview recording both in the information sheet and at the time of the recording, and the process by which they can review the related transcription. *Please note that transcripts of focus groups may raise privacy issues (particularly if the participants are children, since other parents will see comments by children who are not their own).*

INFORMED AND VOLUNTARY CONSENT

Please note: The HEC recommends that participants receive an information sheet, which they must be able to retain, unless there are good reasons for not adopting such a procedure. The information sheet(s) and the consent form(s) should be separate. Projects which **only** involve an anonymous questionnaire may not necessarily require a separate information sheet, provided that the questionnaire includes your name and contact number as well as the other points contained in the information and consent templates available on the HEC website. *Please note: so that participants can retain a copy of the information sheets, the information sheet(s) and the consent form(s) should be separate.*

26. By whom and how will information be given to potential participants? Please attach a copy of the information sheet and consent form (if email/internet, please provide a screen shot), or the oral briefing script. Also, please set out in precise detail the processes used to obtain consent, and ensure that those processes allow the participant the opportunity to say no or withdraw without stress, embarrassment or difficulty. Where you do not intend to gain written consent, (ie, where you will rely on oral consent etc) please justify and explain how you will gain consent.

Interviewees will be invited (by phone or email) to participate in an interview. If they do agree, a time and place is arranged. Consent form and information sheet is provided to the participant ahead of the interview (typically by email) and at the beginning of the interview (in hard copy). It is clarified if the participants would be happy to be named in subsequent research publications or prefer to remain anonymous. If they agree to continue, then one of the research team will lead them through questions (often via a translator) about their experience of the ashfall event, what impacts occurred and how they were managed (see attached question sheet) with another team member writing up their responses. At the completion of the interview, interviewees are invited to review the notes taken by the research team, generally emailed to the participant so they may do so at their leisure.

27. Are all participants competent to give consent on their own behalf? **YES** (delete inapplicable) As a rule, children and young adults under the age of 16 years (or 18 years if still at school) will require parental consent to participate in your research, as do adults who have impairments that limit

their capacity to represent themselves. All such participants unable to give consent should still receive a suitable information sheet and assent form where practicable. It is possible in some cases that respect for the autonomy will override concerns over ethical and legal competency, but these are rare and require much justification, and usually only arise in the context of a general community approval to waive competency requirements.

If no, please explain,
(a) why they are not competent to give informed consent on their behalf?

(b) how consent will be obtained in the absence of that competency?

(c) if applicable, how will assent to participate be gained?

PRIVACY AND CONFIDENTIALITY

28. Will information pertaining to or about the participants be obtained from any source other than the participant? **YES** (delete inapplicable) If yes please state:

(a) the identity of the third party or parties.

Infrastructure and agricultural agencies and small business owners from Chile and Argentina involved in management of ash impacts from the 2015 Calbuco eruption.

(b) why such information is needed.

To access infrastructure and agricultural agencies involved in management of ash impacts from the 2015 Calbuco eruption.

(c) how will you obtain consent from the participant and the third party(ies) to gather that data. Please ensure the information sheet is very clear about any data gathered about participants from third party participants, and how you intend to gain permission to see the data.

The data is being used to set up interviews on the basis of professional relationships and is in line with acting within participant's professional capacities, therefore we consider this to be appropriate.

(d) the processes you will use to obtain that data. If you are using recruitment strategies that access potential participants via a third party please discuss your specific methods here. In general, it is not legal for your participants to give private contact details of other people to you. Usually, should you wish to snowball recruit, you should give your participants an information sheet or advertisement that they can give to others, in the hope that those third parties will then contact you.

It may happen that by virtue of your job, you have right of access to information concerning the participants. Where information has been collected from individuals for a purpose other than your research, it is probable that potential participants will need to be informed that their agreement to participate may involve such use. Guidance on privacy can be found in the polices of the University, and on the website of the Privacy Commissioner.

They will be recommended by our Chilean and Argentinean collaborators while additional participants may be recruited as a result of suggestions from prior interviews/interaction with locals and other facility employees. Interviewees will be invited (by phone or email) to participate in an interview. If they do agree, a time and place is arranged.

29. Is information that identifies participants to be given to any person outside the research team, or if identification of or attribution of comments by participants is sought, please explain how and why. **NO** (delete inapplicable) If yes, please explain how and why and include this in the information and consent forms.

30. Please explain how confidentiality of the participants' identities will be maintained in the treatment and use of the data. eg, the HEC expects that researchers will attempt to ensure that stored data is separated into identifying data (eg, consent forms, coding forms), and de-identified (eg, coded data, de-identified transcripts): typically this is done by assigning participants a code on the consent form, and using that code on any data, transcripts, etc. Where this is too difficult, please explain why.

All recorded notes (notebook and laptop computer) will be kept securely in a concealed compartment within my travel bag that will be kept in a locked room (or vehicle when travelling). Electronic data will be in a password protected folder on our laptop hard drives and backed up on a password protected portable hard drive. Once I (Thomas Wilson) have returned to the University of Canterbury, I will keep the data secured in a locked drawer behind the locked door of my office and on my desktop computer and the portable hard drive in a password protected folder. Data on the laptop will be deleted. The data will be stored for at least 10 years and will subsequently be destroyed.

Data sharing by the research team will be kept within the Department of Geological Sciences, UC, in New Zealand. Researchers will copy the electronic data to their computers – and will follow the same protection protocols as described above. Their field note books with identifying data will be stored in the same locked drawer as my field note books or in their own locked drawers in lockable offices.

Interview data we jointly collect with our collaborator Gustavo Villarosa (Argentina) and Hugo Moreno (Chile) will be stored by them under the same protection protocols as described above (physical materials in locked drawers and office; and electronic files in pass word protected computers).

31. Is an institution (eg, school, business, etc) to which participants belong to be named or be able to be identified in the publication or presentation of this project? **YES** (delete inapplicable) If yes, please explain whether you have made the institution aware of this or why you have decided not to do so.

This form should be completed after reading the *Human Ethics Policy* issued by the Human Ethics Committee available at http://www.canterbury.ac.nz/humanethics

We will make the institution aware of the prior to the commencement of the interview. We will again clarify before publishing the results.

32. Where will the project be conducted? It is recommended that interviews be conducted in public spaces, not in private homes. *The committee appreciates that in some cases there may be good academic reasons for conducting research in private homes. If you believe this applies to your project, we ask you to provide (a) a concise justification of why research in the home is necessary for your project, what alternative locations were considered, and why they were discounted, and (b) detail how you anticipate and will seek to mitigate potential risks to both participants and researchers when undertaking research in a private home(s).*

Mostly in public or private organisation offices. In rare instances, interviews will take place in a private home when a farmers invites us in to their home to discuss the interview questions over tea. It is considered rude to decline such an invitation.

Please note: in the case of research involving children, young adults and participants who need particular care, an adult other than the researcher is required to be present.

RISK

If the answer to any of the following questions is "Yes", please indicate briefly the nature of the risk and what actions you could take, or support mechanisms you could rely on, if a participant should become injured, distressed or offended while taking part in this project. In order to maintain a distinction between the researcher and other roles, support should not be undertaken by researcher. At the very least, a list of support services should be included in the information sheet and also participants made aware of the possibility in the information sheet.

33. Is there any risk to physical well-being? **NO** (delete inapplicable) If yes, describe processes in place to mitigate this/these risk(s).

34. Could participation involve mental stress or emotional distress? **YES** (delete inapplicable) If yes, describe processes in place to mitigate this/these risk(s).

There is a small chance that participants may have experienced mild trauma/stress following recent volcanic activity in the proposed study areas. To mitigate this risk, we will rely on guidance from our local collaborators about who to interview and our own judgement. We also note it is over 12 months since the eruption. Please also refer to the attached list of local support contacts for interview participants – which will be distributed at the commencement of any interview.

35. Is there a possibility of causing moral or cultural offence, inadvertently or otherwise? **YES** (delete inapplicable) If yes, describe processes in place to reduce the possibility of causing such offence, and any consultation/awareness training undertaken.

With any interviews being undertaken in a foreign language there is a risk of giving some cultural offence. We have mitigated this by working closely with local collaborators. Further,

one of our New Zealand based team members, Tyler Barton, volunteered in the field of disaster risk reduction at the community level in Central America where he lived with a community for >1 year and gained experience with conducting interviews and discussion of a similar nature. Additionally, interview topics will be focused on infrastructure or primary industry activities directly related to participant's professional experiences, which they should be familiar with and capable to answer questions in that professional capacity. We have significant experience with each of these topics so will be able to ask appropriate questions in the semi-structured interviews.

36. Is deception involved at any stage of the project? **NO** (delete inapplicable) If yes, please describe the deception, justify its use.

    Please note: the HEC considers the use of title in the documents for the participants that is designed to hide the real aim of the project, a deception however mild.
    Please attach the debriefing sheet or script that you will use to debrief each participant after they have participated in the project or at the end of the project itself. Ensure that the debriefing sheet includes an explicit reminder that the participant can withdraw without penalty given the deception involved.

37. If yes, please describe the deception, justify its use and attach the debriefing sheet or script that you will use to debrief each participant after they have participated in the project or at the end of the project itself. Please ensure that the debriefing sheet includes an explicit reminder that the participant can withdraw without penalty given the deception involved. The use in the information sheet or consent form or questionnaire of a title that differs from the project title given in this application form, in order not to reveal the real aim of the project, is considered to be a form of deception however mild.

DATA STORAGE AND FUTURE USE

38. Please provide details of how the data will be securely stored, and how you will separate identifying and non-identifying data. ie, What steps will be taken to ensure that information given by participants is safe and protected? All storage facilities including electronic equipment should be in rooms that can be locked. All data should be stored in password-protected files and, where on computers, the computers should be password protected. Data should be backed up or stored on the University servers. If you intend to store the data in cloud services please provide a justification and documentary proof that the data will be secure (eg, relevant sections of the terms of service of the provider).

    All recorded notes (notebook and laptop computer) will be kept securely in a concealed compartment within my travel bag that will be kept in a locked room (or vehicle when travelling). Electronic data will be in a password protected folder on my laptop hard drive and backed up on a password protected portable hard drive. Once I have returned to the University of Canterbury I will keep the data secured in a locked drawer behind the locked door of my office and on my desktop computer and the portable hard drive in a password protected folder. Data on the laptop will be deleted. The data will be stored for at least 10

years and will subsequently be destroyed.

Data sharing by the research team will be kept within the Department of Geological Sciences in New Zealand. Researchers will copy the electronic data to their computers – and will follow the same protection protocols as described above. Their field note books with identifying data will be stored in the same locked drawer as my field note books or in their own locked drawers in lockable offices.

Interview data we jointly collect with our collaborator Gustavo Villarosa (Argentina) and Hugo Moreno (Chile) will be stored by them under the same protection protocols as described above (physical materials in locked drawers and office; and electronic files in pass word protected computers).

39. Who, apart from the researcher and their supervisor (where applicable) will have authorised access to the data? Research Assistants and transcribers need their own confidentiality forms and their participation needs to be made known to participants.

Dr. Thomas Wilson – University of Canterbury

Mr. Josh Hayes – University of Canterbury

Dr. Natalia Deligne – GNS Science

Dr. Graham Leonard – GNS Science

Dr. Carol Stewart – Massey University

Mr. Daniel Blake – University of Canterbury

Mr. George Williams – University of Canterbury

Mr. Tyler Barton – University of Canterbury

Dr. Gustavo Villarosa - Universidad Nacional del Comahue, Bariloche, Argentina

Dr. Valeria Outes - Universidad Nacional del Comahue, Bariloche, Argentina

Dr Hugo Moreno – SENERGEOMIN, Chile

40. What will happen to the raw data at the end of the project? Standard HEC principles are that data from research projects will be kept safely and then destroyed as follows:

The data will be stored for at maximum 10 years and will subsequently be destroyed.

At the completion of an Honours or similar project
After 5 years for an MA
After 10 years for a PhD or staff research

Please discuss and justify any variations to these guidelines that your project requires (for instance, if the data is to be kept permanently).
This information should be contained in all information sheets and consent forms.

41. What plans do you have for the publication of the data? Please note, and include in your information sheets, that Masters thesis and PhDs are public documents available via the UC library database. Also, participants should be offered summary of results.

The data will be used for undertaking infrastructure and agriculture impact assessments. It will form the basis of academic peer reviewed journal articles; PhD thesis, public, technical and conference lectures; resources for engineering lifelines organisations to increase their resiliency to volcanic hazards. Participants will be offered a summary of findings if requested.

42. Please describe plans for future use of the data beyond those already described above. **N/A**

This form should be completed after reading the *Human Ethics Policy* issued by the Human Ethics Committee available at http://www.canterbury.ac.nz/humanethics

Departamento de Ciencias Geológicas
Teléfono: +64 3 364 2987 ext 45511
Correo electrónico: thomas.wilson@canterbury.ac.nz

Evaluación de la vulnerabilidad de la infraestructura crítica y las industrias primarias frente de peligros volcánicos en Chile y Argentina

Formulario de consentimiento para participantes del estudio

- ☐ Me han dado una explicación completa de este proyecto y he tenido la oportunidad de pedir más información.
- ☐ Entiendo lo que se requiere de mí si acepto participar en la investigación.
- ☐ Entiendo que mi participación es voluntaria y puedo retirarme en cualquier momento sin penalización. Retirarme incluirá la eliminación de cualquier información proporcionado si es posible de manera práctico.
- ☐ Entiendo que cualquier información u opiniones que doy serán confidenciales para el investigador y que cualquier resultado publicado o reportado no identificará los participantes. Entiendo que una tesis es un documento público y estará disponible a través de la Biblioteca de la Universidad de Canterbury.
- ☐ Entiendo que todos los datos coleccionado para el estudio se mantendrán en instalaciones seguras y / o en forma electrónica protegida con contraseña y serán destruidos tras de diez años.
- ☐ Entiendo los riesgos asociados con mi participación y cómo serán manejados.
- ☐ Entiendo que puedo contactar al investigador (Thomas Wilson – thomas.wilson@canterbury.ac.nz) para obtener más información. Si tengo alguna reclamación, puedo contactar The Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)
- ☐ Si lo pido, puedo obtener un resumen de los resultados del proyecto.
- ☐ Al firmar, acepto participar en este proyecto de investigación.

Nombre:____________________ Firma:____________________ Fecha:__________

Correo electrónico *(para el informe de resultados, si es aplicable)*:________________________

Thomas Wilson

HUMAN ETHICS COMMITTEE

Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2016/69/LR-PS

23 November 2016

Dr Thomas Wilson
Department of Geological Sciences
UNIVERSITY OF CANTERBURY

Dear Thomas

Thank you for submitting your low risk application to the Human Ethics Committee for the research proposal titled "Assessing the Vulnerability of Critical Infrastructure and Primary Industries to Volcanic Ash Fall Hazards in Chile and Argentina".

I am pleased to advise that this application has been reviewed and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 13th November 2016.

With best wishes for your project.

Yours sincerely

pp. R. Robinson

Jane Maidment
Chair, Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. www.canterbury.ac.nz

F E S

Appendix C: The DEVORA scenarios: multi-hazard eruption scenarios for the Auckland Volcanic Field.

Hayes, J.L.; Tsang, S.W.; Fitzgerald, R.H.; Blake, D.M.; Deligne, N.I.; Doherty, A.; Hopkins, J.L.; Hurst, A.W.; Le Corvec N.; Leonard, G.S.; Lindsay, J.M.; Miller, C.A.; Németh, K.; Smid, E.; White, J.D.L.; Wilson, T.M. 2018 The DEVORA scenarios: multi-hazard eruption scenarios for the Auckland Volcanic Field. Lower Hutt, N.Z.: GNS Science. GNS Science report 2018/29. 138 p.; doi: 10.21420/G20652